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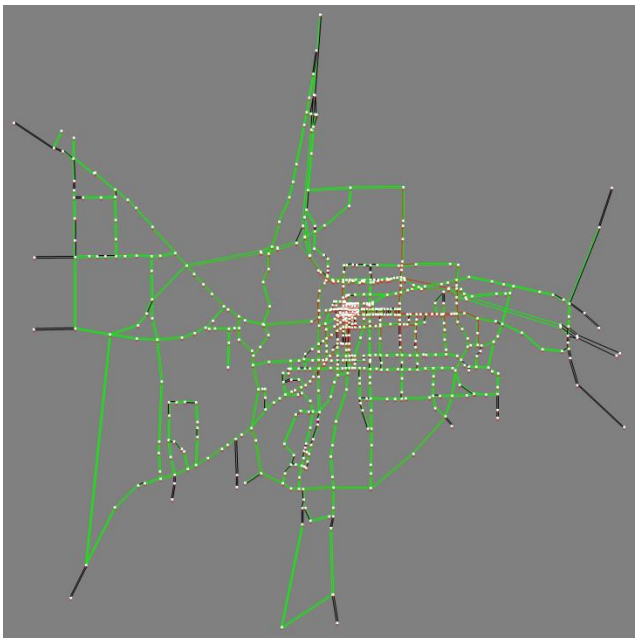

STATEWIDE MESOSCOPIC SIMULATION FOR WYOMING

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16. Abstract

This study developed a mesoscopic simulator which is capable of representing both city-level and statewide roadway networks. The key feature of such models are the integration of (i) a traffic flow model which is efficient enough to scale to large regions, while realistic enough to represent traffic dynamics, including queue growth and dissipation and intersection control; and (ii) a user behavior model in which drivers choose routes based on minimizing travel times. Integrating these models is nontrivial, because route choices depend on route travel times, but route travel times are determined from route choices through the traffic flow model. An iterative approach is used to seek a consistent solution to this problem, using the cell transmission model as the traffic flow model.

These features have been implemented in a software program, for which source code and tutorials have been provided as appendices to this report. Additional modules are provided for generating graphical views of networks, performing warrant analysis based on MUTCD procedures (either to assist with network creation, or as a post-processing step), and a spreadsheet interface to the program itself. Ready-to-use networks have been provided representing the city of Casper and the state of Wyoming.

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SI* (Modern Metric) Conversion Factors

Approximate Conversions from SI Units

Symbol	When You Know	Multiply By	To Find	Symbol
Length				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
Area				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
Volume				
ml	milliliters	0.034	fluid ounces	fl oz
l	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
Mass				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg	megagrams	1.103	short tons (2000 lbs)	T
Temperature (exact)				
°C	Centigrade temperature	1.8 C + 32	Fahrenheit temperature	°F
Illumination				
lx	lux	0.0929	foot-candles	fc
cd/m^2	$candela/m^2$	0.2919	foot-Lamberts	fl
Force and Pressure or Stress				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	pound-force per square inch	psi

Approximate Conversions to SI Units

Symbol	When You Know	Multiply By	To Find	Symbol
Length				
in	inches	25.4	millimeters	Mm
ft	feet	0.305	meters	M
yd	yards	0.914	meters	M
mi	miles	1.61	kilometers	Km
Area				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	Ha
mi^2	square miles	2.59	square kilometers	km^2
Volume				
fl oz	fluid ounces	29.57	milliliters	Ml
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
Mass				
oz	ounces	28.35	grams	G
lb	pounds	0.454	kilograms	Kg
T	short tons (2000 lbs)	0.907	megagrams	Mg
Temperature (exact)				
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celsius temperature	°C
Illumination				
fc	foot-candles	10.76	lux	Lx
fl	foot-Lamberts	3.426	$candela/m^2$	cd/m^2
Force and Pressure or Stress				
lbf	pound-force	4.45	newtons	N
psi	pound-force per square inch	6.89	kilopascals	kPa

Executive Summary

The purpose of this project was to develop a mesoscopic simulation model which can be applied to Wyoming either at the statewide level or the level of individual cities. The main concept behind mesoscopic simulation is to bridge the gap between microscopic simulation, which models small geographic areas (such as a single corridor) with high detail, and macroscopic modeling, which models large geographic areas (such as a state) with relatively little detail. This is particularly important in rural states such as Wyoming, in which a larger share of trips are long-distance, and in which a significant share of freeway volume is out-of-state traffic such as heavy vehicles.

The key to mesoscopic simulation is combining (1) a reasonably simple traffic flow model which can still capture fundamental traffic behavior such as queue growth and dissipation, and signal control at intersections, and (2) a route choice model which reflects drivers' desire to choose the fastest routes to their destinations. These two models interact heavily: for instance, if a major roadway is temporarily closed for a construction project, the route choice model is needed to predict how traffic patterns will shift, but doing so requires knowing how travel times throughout the network will change as well. Briefly, the traffic flow model requires route choices as input and produces travel times, while the route choice model requires travel times as input and produces route choices.

The ultimate goal is to achieve a mutually consistent solution between the traffic flow and route choice modules. In this project, such a system was developed and implemented in the C programming language, with a Microsoft Excel frontend to allow editing and program operation in a more familiar environment. This system is based on iteration between the cell transmission model (the traffic flow model deemed most appropriate after a literature review), a time-dependent version of the A* algorithm (which finds the least travel time route between two points in a network), and the method of successive averages (which adjusts vehicles' route choice based on the updated travel times). Additional modules produce graphical versions of the output data, and perform a warrant analysis to either recommend updated intersection control and signal timing, or generate an initial set of intersection controls and timings when creating a network from scratch.

Three case studies are provided: a small "toy" network to demonstrate the model capabilities; a network representing the city of Casper, under a hypothetical road closure for construction; and a network representing the state of Wyoming, under a hypothetical toll on Interstate 80. For the latter two case studies, "before-and-after" analyses are shown to demonstrate potential applications of the software.

Appendices include more extensive tutorials, a programmer's guide to the simulator, and the C code used to implement the model. In this way, users may continue to modify the software as needed for specific applications.

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Chapter 1

Introduction

The purpose of this project was to develop a mesoscopic simulation model which can be applied to Wyoming either at the statewide level or the level of individual cities. This report documents the research work performed, and includes additional deliverables as appendices. This chapter reviews the motivation behind the project, the primary research accomplishments, and describing how this report is organized.

1.1 Motivation

Traditionally, planning and operations models used by transportation professionals use markedly different assumptions and spatiotemporal scope. By necessity, planning models consider a large geographic area and long-term time horizon, while operational models focus on a smaller region (such as a single corridor and a few alternate routes). This allows the latter greater detail and fidelity at the expense of scope. However, this difference can lead to inconsistency between these models.

For instance, planning models generally do not account for queuing behavior from signals or temporary congestion, and thus may produce link values which are physically implausible and unsuitable for use in microsimulation programs without significant "tweaking" based on engineering judgment. At the same time, microsimulation models cannot give a proper treatment of diversion and rerouting effects, since by their nature they only focus on a portion of most trips, and diversion depends crucially on the origin and destination, not just the portion of the trip included in the microsimulation. This is a particularly significant issue with modeling diversion due to network interruptions (such as work zones), and can help identify necessary changes to traffic control and other operational strategies to mitigate the effects of these disruptions.

Mesoscopic simulation is a promising technique for bridging this gap, using a level of detail intermediate between planning models and microsimulation. Several methods are available to represent traffic flow, and a major part of the project involved selecting the most appropriate

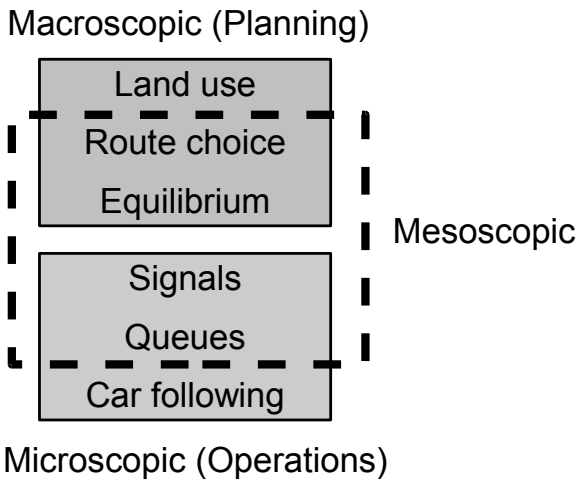


Figure 1.1: Microscopic, mesoscopic, and macroscopic modeling.

model. Particularly, little attention has been paid to the best traffic representation for rural areas. Furthermore, recent advances in computing technology now allows a very large area to be represented in a mesoscopic simulator, even at the statewide level in states with low population density, such as Wyoming.

Mesoscopic simulation adopts a middle ground between the extremes of macroscopic simulation (large area, low detail) and microscopic simulation (small area, high detail), by choosing to represent only the most significant aspects of traffic flow in a computationally efficient manner. The resulting model combines aspects of macroscopic and microscopic modeling, using a consistent set of modeling assumptions (Figure 1.1). Mesoscopic simulation has recently been applied to model traffic flow in major metropolitan areas, including Atlanta, Georgia; Austin, Texas; Dallas-Ft. Worth, Texas; and Chicago, Illinois; but application to rural areas has been lacking even though the transformative potential is just as great, if not more so.

Successfully developing a statewide mesoscopic simulator would benefit WYDOT's current modeling process in several ways:

- Allowing traffic studies to include elements of traditional planning models (such as trip generation, land use, and route choice), leading to more accurate predictions and greater consistency.
- Allowing planning models to benefit from traffic data by serving as a calibration and validation tool, and to generate predicted traffic counts directly from land use models, applied consistently throughout the State.
- Providing WYDOT with a tool which can be used for analysis of policies with statewide implications on traffic flow, such as tolling and its associated diversion effect.

- Creating opportunities for collaboration and data sharing between operations and planning personnel, reducing data collection costs and duplication of effort.

1.2 Primary Accomplishments

In accordance with the proposal, the following primary tasks have been accomplished during the course of this research project:

- A thorough review of the traffic flow theory literature identified the cell transmission model as suitable for statewide, mesoscopic implementation.
- A mesoscopic simulation program has been developed using the C programming language.
- A graphical user interface for the simulator has been developed using Microsoft Excel VBA.
- The simulation program was extended to include basic warrant analysis and signal timing.
- Two Wyoming-specific case studies have been prepared, one for the city of Casper and the other for the entire State.
- Network files for the case studies have been created based on traffic count data and TransCAD files.
- Training tutorials have been developed based on these case studies.
- The C and VBA source code has been documented and provided to WYDOT.

1.3 Outline

The remainder of this report is organized as follows. Chapter 2 presents the engineering concepts underlying the mesoscopic simulator. Chapter 3 explains how these concepts were implemented, using the C language for the simulation code and Microsoft Excel VBA for the interface. Chapter 4 demonstrates this simulation framework, using three examples: a small "artificial" network where all changes can be easily seen; a network representing the city of Casper, before and after a work zone closes a major arterial; and a network representing the state of Wyoming, before and after a toll on I-80. Finally, Chapter 5 concludes the report and identifies an implementation strategy.

Four appendices provide additional deliverables. Appendix A packages the case studies from Chapter 4 in a stand-alone format suitable for training materials. Appendix B provides an overview of the source code organization and data structures, which will be useful for programmers seeking to modify or extend the code. Finally, Appendix D contains the C the simulator and other modules.

Chapter 2

Methodology

2.1 Overview

A mesoscopic simulator contains two equally-important components: a *traffic flow model* which describes the operational nature of traffic flow and delay, and a *user behavior model* which describes how travelers choose their routes. Macroscopic or microscopic simulation tends to focus on one or the other exclusively. Microsimulation software, such as CORSIM or VISSIM, employs a highly realistic traffic flow model, but has a very limited user behavior model, assuming that route flows and turning proportions can be specified exogenously and do not respond to the simulated traffic flow. Macroscopic software, such as TransCAD or VISUM, has a sophisticated user behavioral model which can account for route choice and diversion all throughout a network, but with a much simpler traffic flow model based on unrealistic impedance functions. In a mesoscopic simulator, however, both components are equally important.

This raises the core challenge of mesoscopic modeling: traffic flow and user behavior are closely connected. On the one hand, traffic conditions are determined by the routes that drivers choose to take when they travel. On the other hand, the routes that drivers choose to take are determined by traffic conditions. This circular dependency is indicated schematically in Figure 2.1.

As an example, consider a major maintenance project which will close one or more lanes on a major arterial for several weeks. If no drivers were to change their routes, congestion would arise during the peak period due to the loss of capacity. However, some drivers will divert onto parallel routes (or take entirely different routes, based on their origin and destination). As this happens, congestion will ease somewhat at the work zone location, and perhaps increase slightly along these parallel routes. This in turn will ease the pressure for additional drivers to divert.

Resolving this mutual dependency is the primary methodological challenge in a mesoscopic model. This is accomplished by seeking an *equilibrium* solution, that is, a mutually consistent set of route travel times and route choices. The phrase “mutually consistent” means that the route travel times are exactly those which would occur based on the route choices made, and the route choices are exactly those which would occur based on the route travel times. Under the most

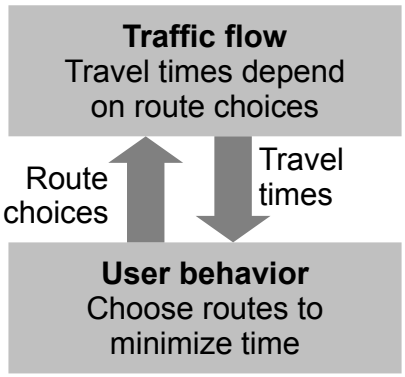


Figure 2.1: Mutual dependency between traffic flow and user behavior.

common assumption — that drivers want to choose the route which minimizes their travel time — the only possible equilibrium solution is one in which all used routes have identical travel time. If any pair of used routes had unequal travel time, drivers would divert from the slower route to the faster one.

This equilibrium principle was first introduced to traffic engineering by Wardrop (1952) and Beckmann Beckmann et al. (1956)[1], which eventually led to the development of macroscopic models such as those in TransCAD or VISUM. However, the traffic flow models used here are exceptionally simplistic, using delay functions which do not reflect the dynamic nature of traffic flow — queues grow and shrink over time (especially at signals), and travel demand varies over time. The main advantage of mesoscopic modeling over this early work is the use of innovative traffic flow models which can account for these dynamics while still being simple enough to apply on large, even statewide, scales.

Finding such an equilibrium involves iteration between the traffic flow and user behavior models. For a given set of route choices, the traffic flow model gives updated route travel times (including any congestion which may arise). Then, the user behavior model updates the route choices as people seek to avoid congestion and divert onto faster routes. Control then returns to the traffic flow model, which updates travel times yet again, and so on until an equilibrium (or near-equilibrium) is found. Since each model must be run multiple times, efficient models are of the utmost importance.

The remainder of this chapter explains the traffic flow model and user behavioral model in greater detail, in Sections 2.2 and 2.3, respectively.

[1] Although this work was prefigured by the economist Pigou (1920)

2.2 Traffic flow model

To be suitable for the project purposes, the chosen traffic flow model must satisfy all of the following conditions. It must be:

1. Scalable to very large regions, including metropolitan areas and statewide networks.
2. Efficient and tractable, not requiring more computational resources than is available on desktop machines.
3. Capable of representing traffic dynamics, in particular how queues grow and dissipate.
4. Capable of representing changes in tripmaking rates over the course of the simulation period.
5. Capable of representing diverse intersection controls (such as signals, stop signs, or grade-separated interchanges).
6. Relatively simple in terms of data input requirements.
7. Transparent in terms of understanding exactly how traffic flow is being propagated, and simple enough to convey to decision-makers and the public.

After a thorough review of the traffic flow literature, the cell transmission model was selected as a model which satisfies these desiderata. The remainder of this section explains the cell transmission model in the context of these criteria, beginning by contrasting it with other well-known traffic flow models, and then deriving the model from the hydrodynamic ("shockwave") theory of traffic flow. These criteria will be repeatedly referred to throughout this section.

2.2.1 Overview of contrasting models

This subsection provides a brief overview of macroscopic and microscopic traffic flow models, to provide context for the description of the cell transmission model which follows.

Macroscopic equilibrium models, such as those used in TransCAD and VISUM, are based on *link performance functions* which report the travel time on a roadway link as a function of the number of vehicles on this link. One standard function was developed by the Bureau of Public Roads (BPR), which has the following form:

$$t = t_0 \left(1 + \alpha \left(\frac{x}{c}\right)^{\beta}\right) \tag{2.1}$$

where t is the travel time on a roadway link, t_0 is the free-flow travel time, x and c are the roadway volume and capacity, and α and β are parameters which can be calibrated to date.

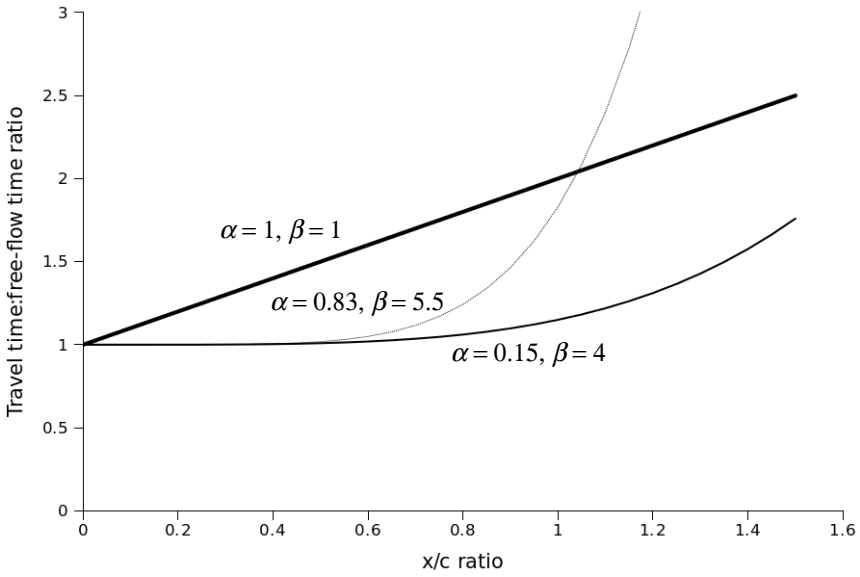


Figure 2.2: BPR functions with different α and β values.

Figure 2.2 shows different BPR functions based on the values of α and β. The most typical choices in practice are $\alpha = 0.15$ and $\beta = 4$.

The advantage of this formulation is that it lends itself to easy solution even on very large networks. Consider a large network with a set of roadway links A, a set of intersection nodes N, and a set of centroid nodes $Z \subseteq N$. Let t_{ij}, x_{ij}, and c_{ij} be the travel time, volume, and capacity on each link, and d^{rs} is the travel demand from origin $r \in Z$ to destination $s \in Z$. Let Π^{rs} be the set of routes between centroids r and s, and h^{π} the number of drivers choosing route π. Then the equilibrium solution solves the following mathematical optimization problem Beckmann et al. (1956):

$$\min_{\mathbf{x},\mathbf{h}} \quad \sum_{(i,j)\in A} \int_0^{x_{ij}} t_{ij}(x)dx \tag{2.2}$$

$$\text{s.t.} \quad x_{ij} = \sum_{(r,s)\in D} \sum_{\pi\in\Pi^{rs}:(i,j)\in\pi} h^{\pi} \qquad \forall (i,j) \in A \tag{2.3}$$

$$d^{rs} = \sum_{\pi\in\Pi^{rs}} h^{\pi} \qquad \forall (r,s) \in Z^2 \tag{2.4}$$

$$h^{\pi} \geq 0 \qquad \forall \pi \in \bigcup_{(r,s)\in D} \Pi^{rs} \tag{2.5}$$

There are many algorithms which can solve this optimization program very efficiently, even for networks with tens of thousands of links. For an overview of such algorithms, see Patriksson (1994) or Boyles and Waller (2010).

However, the use of link performance functions as the traffic flow model has several significant shortcomings. Referring to the list of criteria in the previous section, it fails to satisfy Criteria 3,

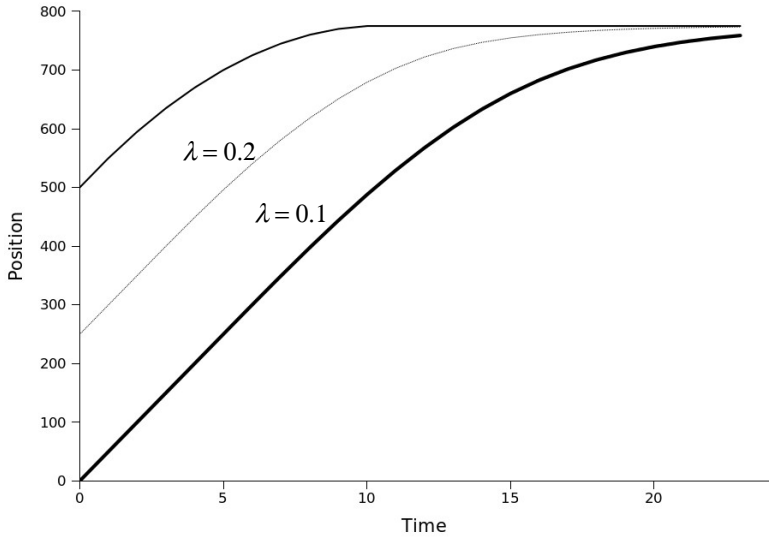


Figure 2.3: Car following with different λ values, $T = 1$.

4, and 5: there is no concept of time dynamics in this model, either regarding the evolution of network conditions or of travel demand. Furthermore, this model is extremely limited in how it can reflect intersection dynamics, because the travel time functions t_{ij} only depend on the flow on that specific link. By contrast, intersection delays typically depend on the flow from conflicting movements, depending on the control type. Perhaps more seriously, there is nothing in the model which enforces $x_{ij} \leq c_{ij}$, that is, that volumes be less than capacity! It should be clear that such functions cannot represent the realities of traffic flow at anything more than a very approximate level.

Microscopic simulation, on the other hand, is usually based on the concepts of car following and gap acceptance. Car following models describe how vehicles move in a traffic stream. Let $z(t)$ describe the position of a vehicle at time t, and $z'(t)$ describe the position of the vehicle immediately in front of it. A basic car following model is

$$\frac{\partial^2 z}{\partial t^2}(t+T) = \lambda \left(\frac{\partial z'}{\partial t} - \frac{\partial z}{\partial t} \right) \tag{2.6}$$

where T is the reaction time of a driver. In other words, the acceleration of a vehicle is proportional to the relative velocity between that vehicle and the vehicle in front of it. The parameter λ can be calibrated to data to reflect the strength of this response; see Figure 2.3 Experiments place the value of λ in practice at approximately 1/3; if $T\lambda < 1/2$, the overall stream of traffic is stable with respect to disturbances.

More sophisticated car-following models have been proposed, taking into account potential coupling between vehicles further ahead, the spacing, and other factors. The primary advantage of these models is their ability to easily represent different vehicle types and driver-specific behavior. A disadvantage is that solving these models requires either the solution of complex

partial differential equations, or numerical simulation which is difficult to analyze.

Models for yielding behavior at intersections or merges is generally based on the theories of gap acceptance and queueing theory. When traffic streams intersect, as at a merge or two-way stop, vehicles in one stream must yield the right of way to another. In such cases, vehicles in the minor stream must wait for gaps of sufficient size to appear in the major stream. Let t_c and t_f denote the *critical gap* and *follow-up gap*, respectively, both measured in seconds. The critical gap is the smallest gap in the major stream that a vehicle is willing to accept; the follow-up gap is the additional time required for subsequent vehicles to follow the first vehicle to move during a gap. We generally observe $t_f \leq t_c$. Assuming that headways in the primary stream are exponentially-distributed, one can show that the capacity on the minor approach is given by

$$c = \frac{x_M \exp(-x_M t_c)}{1 - \exp(-x_M t_f)} \tag{2.7}$$

In simulation, individual gaps will be tracked, and the appropriate number of vehicles moved.

While these car-following and gap-acceptance models can be used to model traffic very realistically, like the macroscopic models they do not satisfy all of the criteria listed above. While they can model traffic dynamics, they do not satisfy criteria 1 and 2 because they do not scale well to larger regions. Accurate simulation using these models requires a very fine time step (typically on the order of a tenth of a second) and knowing the exact location of every vehicle on the network during each step.

What is needed is a model which can account for traffic dynamics, while requiring less spatiotemporal precision than the microscopic models. The cell transmission model satisfies all necessary criteria. Before presenting this model, the hydrodynamic theory of traffic flow is reviewed, since this forms the theoretical basis for the cell transmission model.

2.2.2 The hydrodynamic theory

The hydrodynamic theory of traffic flow was independently derived by Lighthill and Whitham (1955) and Richards (1956); it is often referred to as the LWR model. This theory is a *continuum model* or *fluid model* — rather than modeling vehicles as separate, discrete entities, the LWR model approximates traffic flow as a continuous fluid, and applies results similar to those in fluid dynamics. There are three key variables which describe the traffic stream at any location x and time t: the *density* k, the *flow* q (also known as the *volume*), and the *speed* u. Density is measured in vehicles per unit length (often vehicles per mile), and flow is measured in vehicles per unit time (often vehicles per hour). These three variables are related by the *fundamental equation* $q = uk$, which must hold at any point and time.

The LWR theory makes two additional postulates. The first is that the flow at a point depends only on the density at that point, that is, that

$$q(x,t) = Q(k(x,t)) \tag{2.8}$$

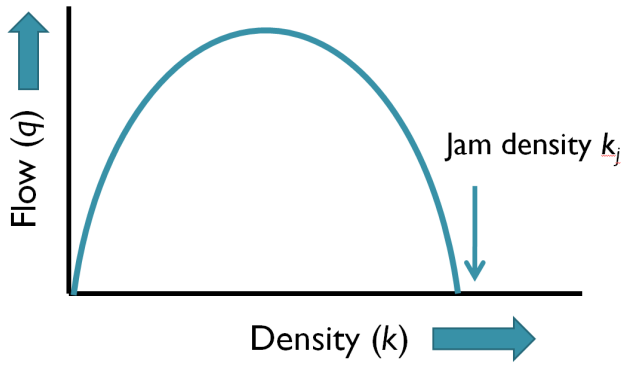


Figure 2.4: A typical fundamental diagram.

for some function Q. This function is known as the *fundamental diagram*. It is typically continuous, concave, and has two zeros: one at $k = 0$, and the other at the *jam density* $k = k_j$. In other words, there are two possible reasons for zero flow: either there are no vehicles and $k = 0$, or traffic is completely jammed and no vehicles are moving, and therefore $k = k_j$. A typical fundamental diagram is shown in Figure 2.4.

The second major postulate of the LWR theory is a conservation law, which states that vehicles cannot "appear" or "disappear" in the network (except for when departing from an origin or arriving at a destination). To enforce this, let $N(x, t)$ represent the *cumulative count* at location x and time t, that is, the total number of vehicles which have passed point x from the start of the modeling period until time t. Under the fluid assumption, $N(x, t)$ is a continuous function. Note that the cumulative count is related to the flow and density. In particular

$$q(x, t) = \frac{\partial N}{\partial t} \tag{2.9}$$

and

$$k(x, t) = -\frac{\partial N}{\partial x} \tag{2.10}$$

where the negative sign in the latter equation reflects the sign convention used: x increases in the direction of flow. Therefore, at any point x, the cumulative count increases as t increases; but at any time t, the cumulative count *decreases* as we move in the direction of increasing x. If N is twice continuously differentiable, then

$$\frac{\partial^2 N}{\partial x \partial t} = \frac{\partial^2 N}{\partial t \partial x} \tag{2.11}$$

or, substituting (2.10) and (2.9) and rearranging, we have

$$\frac{\partial q}{\partial x} + \frac{\partial k}{\partial t} = 0 \tag{2.12}$$

This is the conservation law in the LWR model.

It may not be clear why this derivation expresses the conservation of vehicles, so a geometric argument is presented to help clarify this interpretation. Consider the region of (x, t) space in

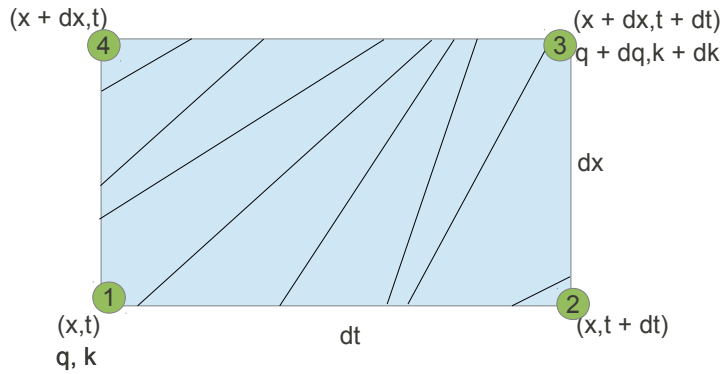


Figure 2.5: Deriving the conservation equation.

Figure 2.5, which has duration dt and spatial extent dx. Let $N(x,t) = N_0$, and assume that the values of $q \equiv q(x,t)$ and $k \equiv k(x,t)$ are known. Similarly, let $q(x+dx, t+dt) = q + dq$ and $k(x+dx, t+dt) = k + dk$. Then, moving to point 2, $N(x, t+dt) = N_0 + q\ dt$ because of (2.9). Moving from point 2 to point 3 and applying (2.10), we have

$$N(x+dx, t+dt) = N(x, t+dt) - (k+dk)dx = N_0 + q\ dt - (k+dk)dx \tag{2.13}$$

Moving from point 3 to point 4, we have

$$N(x+dx, t) = N(x+dx, t+dt) - (q+dq)dt = N_0 + q\ dt - (k+dk)dx - (q+dq)dt \tag{2.14}$$

And finally, moving from point 4 to point 1, we have

$$N(x,t) = N(x+dx, t) + k\ dx = N_0 + q\ dt - (k+dk)dx - (q+dq)dt + k\ dx \tag{2.15}$$

But we already know $N(x,t) = N_0$. Therefore $q\ dt - (k+dk)dx - (q+dq)dt + k\ dx = 0$, or equivalently,

$$\frac{\partial q}{\partial x} + \frac{\partial k}{\partial t} = 0 \tag{2.16}$$

This equation was derived using a conservation principle: that if we move around a closed curve, the value of N should not change when we return, because all vehicles are accounted for.

Therefore, the LWR model can be formulated as the solution to a system of partial differential equations: in particular, finding functions $N(x,t)$, $q(x,t)$, and $k(x,t)$ such that

$$q(x,t) = \frac{\partial N(x,t)}{\partial t} \tag{2.17}$$

$$k(x,t) = -\frac{\partial N(x,t)}{\partial x} \tag{2.18}$$

$$q(x,t) = Q(k(x,t)) \tag{2.19}$$

given a set of boundary conditions (for instance, link inflow rates, or constraints on outflows due to a signal).

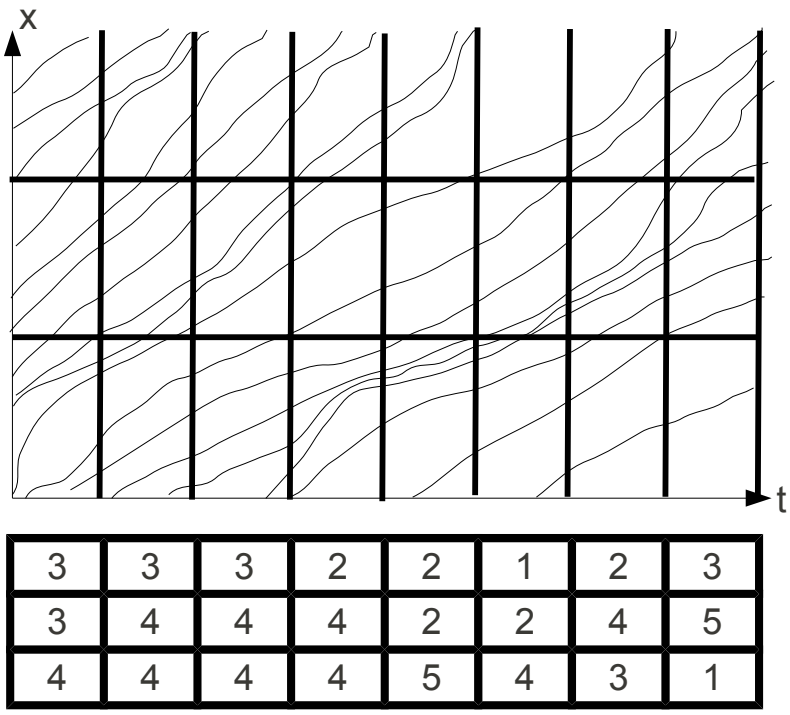


Figure 2.6: Cell discretization of a trajectory diagram.

2.2.3 Cell transmission model

In general, it is difficult to solve the system of partial differential equations (2.17)–(2.19). However, the cell transmission model (Daganzo, 1994) provides an extremely simple way to solve this system for a particular fundamental diagram Q. Furthermore, the final formulas are in fact quite simple (keeping in mind Criterion 7) and easy to interpret in terms of physical traffic flow. The cell transmission model involves two major steps. First, space and time are discretized into "cells", and the LWR model is reformulated in terms of the number of vehicles moving from one cell to the next during a time step. Second, the fundamental diagram Q is approximated as piecewise-linear (trapezoidal).

Figure 2.6 shows how the discretization functions. The top panel of this figure shows a trajectory diagram, in which each thin line represents the path a vehicle takes (its x coordinate at each time t). The thick horizontal and vertical lines are drawn at regular spacings Δt and Δx, respectively. The bottom panel shows how the cell transmission model would represent this traffic flow: rather than tracking the individual locations of all vehicles at all points in time, it suffices to track the number of vehicles in each cell during each time interval; denote this by $n(x,t)$, and let $y(x,t)$ be the number of vehicles flowing through cell x at time t.

Calculations are greatly simplified by assuming a trapezoidal fundamental diagram, as shown in Figure 2.7. This is in keeping with Criterion 6, regarding data input requirements — a trapezoidal

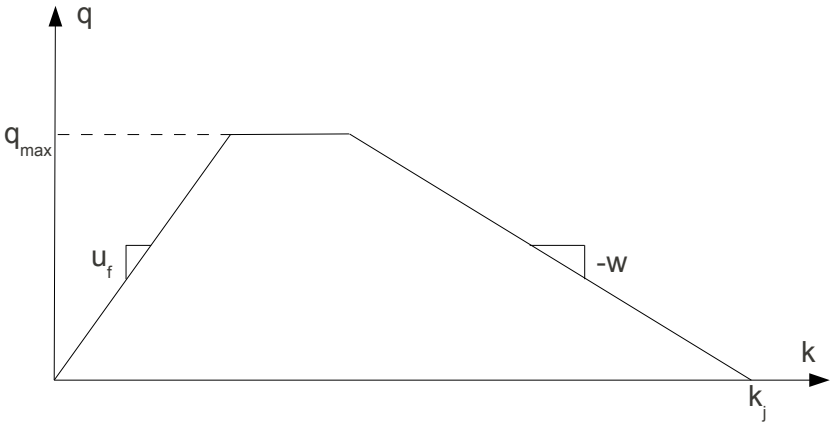


Figure 2.7: The trapezoidal fundamental diagram.

fundamental diagram is completely specified by four parameters, three of which are calculated routinely by traffic engineers. These are u_f, the free-flow speed on a roadway link; Q_{max}, the roadway capacity; k_j, the roadway jam density; and w, the speed at which backward-moving shockwaves travel[2]. u_f and Q_{max} are routinely calculated using procedures such as those in the Highway Capacity Manual (Transportation Research Board, 2010). k_j is typically estimated based a typical front bumper-to-front bumper spacing of vehicles when stopped (say, 20 ft) and the number of lanes. Only w is difficult to calibrate, but experience shows that w is roughly 1/3 to 1/2 of u_f. A key feature of this diagram is that travel speeds do not drop below the free-flow speed until the roadway capacity is reached. This trapezoidal diagram can be mathematically represented by the equation:

$$Q(k) = \min\{u_f k, Q_{max}, w(k_j - k)\} \tag{2.20}$$

The cell transmission model makes one further assumption, that the space and time discretizations are related:

$$\Delta x = u_f \Delta t \tag{2.21}$$

that is, the length of each cell is the distance a vehicle would travel at the free-flow speed. This simplifies calculations in two relatively intuitive ways, and in one deeper way. First, no vehicle can ever cross more than one cell boundary between ticks; to see how many vehicles may enter a cell during a time interval, one only need look at the cell immediately upstream. Second, if there is no congestion, *all* of the vehicles in each cell can proceed to the next. More deeply, the solution method presented next actually solves the system of partial differential equations (2.17)–(2.19) using what is known as a Godunov scheme; for such a scheme to be numerically stable, Δx and Δt must satisfy the Courant-Friedrichs-Lewy condition. One can show that choosing these values using equation (2.21) satisfies this condition, and thus proves the stability of the cell transmission model. The interested reader is referred to Godunov (1959) and Courant et al. (1928) for more details.

[2]For instance, consider a roadway where traffic is flowing at capacity. If a traffic signal turns red, the back of the queue will travel upstream at speed w.

Using this discretization, $n(x,t) = k(x,t)\Delta x$ and $y(x,t) = q(x,t)\Delta t$. We can then calculate $y(x,t)$ as follows, introducing $N(x,t) = k_j \Delta x$ as the maximum number of vehicles which can fit into a cell, and $\delta = w/u_f$ as the ratio of the backward wave speed to free-flow speed (typically 1/3–1/2):

$$
\begin{aligned}
y(x,t) &= q\left(x,t\right)\Delta t && (2.22)\\
&= Q\left(k\left(x,t\right)\right)\Delta t && (2.23)\\
&= Q\left(\frac{n\left(x,t\right)}{\Delta x}\right)\Delta t && (2.24)\\
&= \min\left\{u_f \frac{n\left(x,t\right)}{\Delta x}, Q_{max}, w\left(k_j - \frac{n\left(x,t\right)}{\Delta x}\right)\right\}\Delta t && (2.25)\\
&= \min\left\{u_f n(x,t)\frac{\Delta t}{\Delta x}, Q_{max}\Delta t, w\left(N(x,t) - n(x,t)\right)\frac{\Delta t}{\Delta x}\right\} && (2.26)\\
&= \min\left\{n(x,t), Q_{max}\Delta t, \delta\left(N(x,t) - n(x,t)\right)\right\} && (2.27)
\end{aligned}
$$

where the last equality is obtained using (2.21). Equation (2.27) is the key equation in the cell transmission model, and describes how many vehicles can pass through cell x at time t. Despite its somewhat intimidating appearance, the equation actually has a very intuitive interpretation. The flow through a cell can be limited by one of three things:

1. The number of vehicles in the cell (because no vehicle can travel more than one cell at a time).
2. The capacity of the cell.
3. The available space in the cell, if it is congested.

The three terms in the minimization in (2.21) correspond exactly to these three criteria: if the cell is uncongested, the maximum flow is $n(x,t)$, the number of vehicles in the cell; at all times, the cell capacity must be obeyed, and no more than $Q_{max}\Delta t$ vehicles may pass through; if the cell is congested, the amount of free space $N(x,t) - n(x,t)$ in the cell is what controls the flow. The goal of the cell transmission model, then, is to simulate the movement of vehicles from one cell to another, taking into account these three possible flow regimes (uncongested flow, capacity flow, and congested flow).

2.2.4 Traffic flow on a roadway link

Each roadway link is divided into a number of cells, based on the free flow time and time discretization. As a concrete example, consider a 30-second time discretization ($\Delta t = 30$ s) on a roadway which is one mile long and has a free-flow speed of 30 mph, capacity of 2000 vehicles per hour, and jam density of 240 vehicles per mile. At 30 mph, a vehicle can travel a quarter of a mile in 30 seconds; therefore, this link would be divided into four cells (Figure 2.8). Let $i \in \{1,2,3,4\}$ index these four cells.

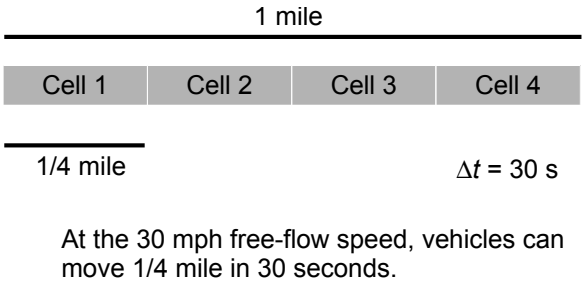


Figure 2.8: Division of a link into cells.

Let $y_{ij}(t)$ denote the number of vehicles which flow out of cell i and into cell j during time t. (Every vehicle must always be in a cell; it cannot exit cell i until it enters cell j.) Let $S_i(t)$ denote the *sending flow*, that is, the maximum number of vehicles which can leave cell i during time interval t

$$S_i(t) = \min\{n(i,t), Q_{max}\Delta t\} \tag{2.28}$$

and $R_i(t)$ the *receiving flow*, that is, the maximum number of vehicles which can enter cell i during time interval t:

$$R(i)(t) = \min\{\delta(N(i,t) - n(i,t)), Q_{max}\Delta t\} \tag{2.29}$$

Since a vehicle cannot flow from between cells i and j unless it can both be sent from i and received at j, we have

$$y_{ij}(t) = \min\{S_i(t), R_j(t)\} \tag{2.30}$$

The number of vehicles in each cell can then easily be calculated for the next time interval:

$$n(i, t+1) = n(i,t) + y_{i-1,i}(t) - y_{i,i+1} \tag{2.31}$$

that is, the previous number of vehicles in the cell, adding the number of vehicles which entered from the upstream cell, and subtracting the number of vehicles which left for the downstream cell. Note that flow into the first cell, and out of the last cell, cannot be handled by these formulas (since the cells $i-1$ or $i+1$ are out of range). Instead, they depend on the flow model at intersections, which is the topic of the next subsection.

2.2.5 Traffic flow at intersections

Roadway links meet at intersections, and the goal of intersection models is to move flow from the downstream ends of incoming roadway links onto the upstream ends of outgoing roadway links, accounting for any traffic control at the intersection (such as stop signs or traffic signals). There are two main ways to represent intersection flow: explicit simulation and implicit simulation. In the first method, explicit simulation, gap acceptance and the red and green indications of traffic signals are directly simulated in the model. With implicit simulation, the "average" effect of traffic control (given the current flow patterns and capacities) is simulated, without modeling each

gap and change of signal phase. As Yperman (2007) explains, there are three major disadvantages to explicit simulation:

1. Explicit simulation can require a small value of Δt. For instance, if a short protected left-turn phase only provides 5 seconds of green, then Δt can be no greater than 5 seconds. Since small values of Δt greatly increase the computational burden of running a simulation model, even one intersection with a short signal phase can dramatically affect memory and time requirements (cf. Criterion 2) when using explicit simulation.

2. The main goal of mesoscopic simulation is to integrate traffic flow and driver behavior. However, when drivers choose routes, they base their decision on the *average* travel times, and do not time their departure time based on anticipated signal phases at arrival. (That is, no driver would think "I need to leave at 8:15 and 30 seconds so I can catch the signal at First and Main just as it turns green.") Explicitly simulating signal phases *over-optimizes* the model in the sense that it introduces more detail than drivers would actually account for in real life, which leads to unnecessary complication and increased computational burden.

3. Field conditions exhibit stochasticity and randomness, so that even if drivers wanted to time departures and arrivals exactly based on signal phasing, they would be unable to do so, due to fluctuations in driver speed, vehicles turning in and out of driveways, and so forth. Therefore it makes more sense to simulate average conditions.

For these reasons, the implicit simulation approach is preferred for mesoscopic simulation.

The remainder of this subsection describes how general intersection of any type are handled. Diverges (one incoming link, multiple outgoing links) are first discussed, followed by merges (multiple incoming links, one outgoing link and general intersections (with any number of incoming and outgoing links). Diverges and merges form the "prototype" models upon which the general intersection model is built. In all cases, the intersection models *only* depend on (a) the sending flow from the downstream cell on all incoming links; (b) the receiving flow for the upstream cells on all outgoing links; and (c) additional intersection-specific parameters (such as cycle length).

Diverges A diverge intersection is one with only one incoming link (labeled u, for upstream), but more than one outgoing link (here labeled 1 and 2), as in Figure 2.9. Our interest is calculating the rate of flow from the upstream link to the downstream ones, that is, the flow rates y_{u1} and y_{u2}.The upstream sending flow S_u and downstream receiving flows R_1 and R_2 will play a central role. For the first time, we also need to represent some model of *route choice*, since some drivers may choose link 1, and others link 2. Let p_1 and p_2 be the proportions of drivers choosing these two links, respectively. Naturally, p_1 and p_2 are nonnegative, and $p_1 + p_2 = 1$. These values can change with time.

There are two possibilities, one corresponding to free flow conditions at the diverge, and the other corresponding to congestion. For the diverge to be freely flowing, *both* of the downstream links must be able to accommodate the flow which seeks to enter them. The rates at which vehicles

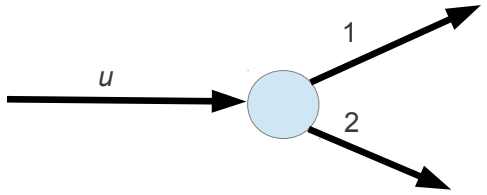


Figure 2.9: Prototype diverge intersection.

want to enter the two links are $p_1 S_u$ and $p_2 S_u$, so if both downstream links can accommodate this, we need $p_1 S_u \leq R_1$ and $p_2 S_u \leq R_2$. In this case we simply have $y_{u1} = p_1 S_u$ and $y_{u2} = p_2 S_u$: all of the flow which wants to leave the diverge can.

In the congested case, One common assumption is that flow waiting to enter one link at a diverge will obstruct every other vehicle on the link (regardless of which link it is destined for). This most obviously represents the case where the upstream link has only a single lane, so any vehicle which has to wait will block any vehicle behind it; but this model is commonly used even in other cases. When there is congestion, only some fraction ϕ of the upstream sending flow can move. The assumption that any vehicle waiting blocks every vehicle upstream implies that this same fraction applies to both of the downstream links, so $y_{u1} = \phi p_1 S_u$ and $y_{u2} = \phi p_2 S_u$.

The inflow rate to a link cannot exceeds its receiving flow, so $q_{u1} = \phi p_1 S_u \leq R_1$ and $q_{u2} = \phi p_2 S_u \leq R_2$, or equivalently $\phi \leq R_1/p_1 S_u$ and $\phi \leq R_2/p_2 S_u$. Every vehicle which can move will, so

$$\phi = \min \left\{ \frac{R_1}{p_1 S_u}, \frac{R_2}{p_2 S_u} \right\} \tag{2.32}$$

Furthermore, we can introduce the uncongested case into this equation as well, and state

$$\phi = \min \left\{ \frac{R_1}{p_1 S_u}, \frac{R_2}{p_2 S_u}, 1 \right\} \tag{2.33}$$

regardless of whether there is congestion at the diverge or not. If the diverge is at free flow, then $\phi = 1$, but $R_1/p_1 S_u \geq 1$ and $R_2/p_2 S_u \geq 1$. Introducing 1 into the minimum therefore gives the correct answer for free flow. Furthermore, if the diverge is not at free flow, then either $R_1/p_1 S_u < 1$ or $R_2/p_2 S_u < 1$, so adding 1 does not affect the minimum value. Therefore, this formula is still correct even in the uncongested case.

This formula easily generalizes to more than one outgoing link. If D is the set of downstream links (indexed by d), the general diverge flow formula is

$$y_{ud}(t) = p_d S_u \min_{d' \in D} \left\{ \frac{R'_d}{p'_d S_u}, 1 \right\} \qquad \forall d \in D \tag{2.34}$$

where $\sum_{d \in D} p_d = 1$ and $p_d \geq 0$ for all d.

Merges A merge intersection has only one outgoing link (labeled d, for downstream), but more than one incoming link (here labeled 1 and 2), as in Figure 2.10. We want to calculate the rate of

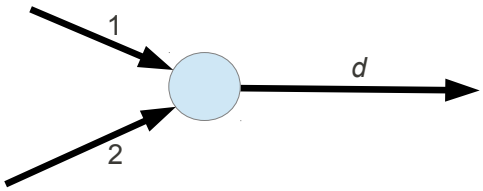


Figure 2.10: Prototype merge intersection.

flow from the upstream links to the downstream one, that is, the flows y_{1d} and y_{2d}. The main quantities of interest are the upstream sending flows S_1 and S_2, and the downstream receiving flow R_d. Unlike diverges, there is no route choice here, so there are no p values.

There are three possibilities, one corresponding to free flow conditions at the merge, one corresponding to congestion with queues growing on both upstream links, and one corresponding to congestion on only one upstream link. For the merge to be freely flowing, both upstream links must be able to transmit all of the flow which seeks to leave them, and the downstream link must be able to accommodate all of this flow. Mathematically, we need $S_1 + S_2 \leq R_d$, and if this is true then $q_{1d} = S_1$, and $q_{2d} = S_2$.

In the second case, there is congestion (so $S_1 + S_2 > R_d$), and furthermore, flow is arriving fast enough on both upstream links for a queue to form at each of them. Empirically, in such cases the flow rate from the upstream links is proportional to the capacity on these links, that is,

$$\frac{y_{1d}}{y_{2d}} = \frac{Q^1_{max}}{Q^2_{max}} \tag{2.35}$$

Furthermore, in the congested case, all of the available downstream capacity will be used, so

$$y_{1d} + y_{2d} = R_d \tag{2.36}$$

Substituting (2.35) into (2.36) and solving, we obtain

$$y_{id} = \frac{Q_i^{max}}{Q_1^{max} + Q_2^{max}} R_d \tag{2.37}$$

for $i \in \{1, 2\}$. Note that this method does not explicitly refer relative priorities, as might be given by a yield sign or roundabout control. The reason is that repeated field data show that vehicles tend to "take turns" merging during congestion, regardless of the rules of the road.

The third case is perhaps a bit unusual. The merge is congested ($S_1 + S_2 > R_d$), but a queue is only forming on one of the upstream links. This may happen if the flow on one of the upstream links is much less than the flow on the other. In this case, the proportionality rule allows all of the sending flow from one link to enter the downstream link, with room to spare. This "spare capacity" can then be consumed by the other approach. Mathematically, if one link cannot send enough flow to meet the proportionality condition, then for exactly one $i \in \{1, 2\}$ we have

$$y_{id} < \frac{Q_i^{max}}{Q_1^{max} + Q_2^{max}} R_d$$

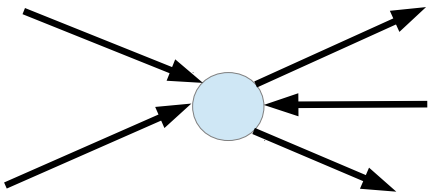


Figure 2.11: General intersection with multiple approaches and exits.

So, if j is the "other" link ($j \in \{1, 2\}$ but $j \neq i$), the two flow rates are $y_{id} = S_i$ and $y_{jd} = R_d - S_i$: one link sends all of the flow it can, and the other link consumes the remaining capacity.

The case of more than two upstream links is handled in a similar fashion. The objective is to determine which approaches (if any) will have queues; the approaches without queues can move their entire sending flow, while the approaches with queues can move sending flow in proportion to their capacity. While it is cumbersome to write analytical formulae for these cases, an iterative algorithm can determine these approaches quite efficiently, as described in Chapter 3.

General intersections General intersections consist of any number of incoming and outgoing links, and the procedure for determining flows for these are now described. Figure 2.11 shows an intersection with several incoming and outgoing links. Note that a *turning movement* cell has been created for every possible movement in this intersection. (If a turning movement does not connect an incoming link to an outgoing link, then that movement is considered forbidden, as with a turn prohibition).

Turning movement cells are slightly different than the ordinary cells which comprise roadway links, in several ways. First, the capacity of a turning movement cell can potentially change based on intersection conditions, to represent turning movements which must yield to another. Second, each turning movement has a *target delay*, that is, an average amount of time that vehicles are delayed when making this turning movement, due to intersection control (signal or stop). Note that this delay does *not* account for additional delay due to downstream congestion; it *only* measures delay due to the intersection control itself.

Each turning movement cell has its own sending flow — the number of vehicles in that cell that have been there longer than the target delay — and its own receiving flow, equal to the minimum of the turning movement's saturation flow, and that movement's share of the downstream roadway link's receiving flow. The intersection algorithm proceeds as follows:

1. Calculate the sending flow for each turning movement cell.
2. For each outgoing link j:
   (a) Calculate the receiving flow for link j.
   (b) Treat all turning movements ij with j as downstream link as a merge, calculate temporary flows y'_{ij}.

(c) Set the receiving flow of turning movement cell ij to y'_{ij}.

3. Load vehicles onto turn movement cells. Repeat the following steps for each incoming link i:

   (a) Calculate the sending flow for link i.

   (b) Treating link i as a diverge, move vehicles onto all turning movements ij with i as upstream link.

4. Move vehicles out of turn movement cells:

   (a) Recalculate the sending flow for each turning movement cell.

   (b) For each outgoing link j:

      i. Calculate the receiving flow for link j.

      ii. Treat all turning movements ij with j as downstream link as a merge, and move vehicles.

2.3 User behavior model

In contrast to the traffic flow model, the user behavior model is relatively simple, and is based on the principle of user equilibrium: if every driver is choosing a route that minimizes their own travel time, then all used routes connecting the same origin and destination will have equal and minimal travel time. Otherwise, one or more drivers would switch from a route with higher travel time to a route with a lower travel time, and the travel times on those two routes would tend to equalize.

Let Z denote the set of *centroids*, special intersections where all trips begin and end. (In software such as VISSIM, they are called "parking lots.") Vehicles cannot pass through a centroid unless they are starting or ending there. Let r and s be centroids. The notation d^{rs} denotes the total number of vehicles departing centroid r for destination s during the analysis period. This value is provided as an input, and can be generated from a travel demand model such as that used by metropolitan planning organizations.

For mesoscopic simulation, this total demand must be *profiled*, or distributed, across the analysis period. Several different profiles are possible; see Figure 2.12 for a few possibilities. In the absence of further information, a uniform profile is a reasonable choice. In practice, field data can be used to calibrate the profile to match observed traffic counts or travel times. This profiling process produces values $d^{rs}(t)$, that is, the number of trips departing r for destination s *during time period* t; naturally $\sum_t d^{rs}(t) = d^{rs}$.

The user behavior model must now assign each of these $d^{rs}(t)$ vehicles to some route connecting centroids r and s, and do this for each time interval t. Using the notation from the macroscopic equilibrium formulation, let Π^{rs} denote the set of all routes connecting r to s, and let $h^{\pi}(t)$ denote the number of trips departing on path π at time t. Let $\tau^{\pi}(t)$ denote the travel time on route π for

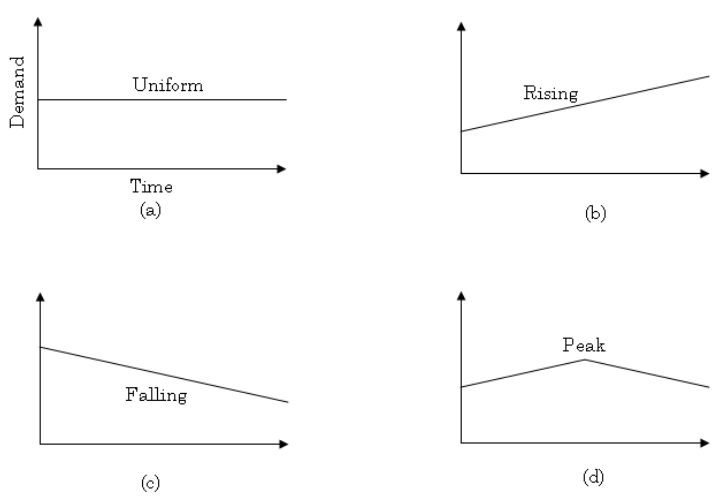


Figure 2.12: Four possible demand profiles.

travelers leaving at time t. Additionally define $\mathbf{h}$ and $\boldsymbol{\tau}$ to be the vectors of route flows and travel times across all r, s, and t.

Given any value of $\mathbf{h}$, the traffic flow model can determine $\boldsymbol{\tau}(\mathbf{h})$ — if the number of people leaving each route at each time is determined, calculating travel times is a simple matter of simulating the resulting traffic patterns (including any congestion) with the cell transmission model. The question now is how to update $\mathbf{h}$ to move towards an equilibrium solution. Since all drivers want to choose the route with the lowest travel time, we can define a "target" route flow vector $\mathbf{h}^*(\boldsymbol{\tau})$ in which every driver chooses the fastest route available to him or her based on travel times $\boldsymbol{\tau}$.

Of course, if all drivers switch to these target routes, the travel times will likely change and those routes will no longer have the fastest travel time. Instead, the solution is to switch only some drivers from their current routes onto the target routes. For any $\xi \in [0, 1]$, the vector $\xi\mathbf{h}^* + (1 - \xi)\mathbf{h}$ represents a set of route choice decisions intermediate between the current choices and the target choices, with ξ representing the proportion of drivers switching. (If $\xi = 0$, no drivers switch from their current routes; if $\xi = 1$, all drivers switch; if $\xi = 1/2$, half of drivers switch, and so forth.) In this way, we can avoid "overcorrecting" by moving too many people onto the same path at the same time, before recalculating travel times using the traffic flow model and making another route choice adjustment.

There are several compromises which must be made in choosing the right value of ξ. If you pick a value which is too small, very few drivers will switch paths, and the travel times will be very similar to what they were before. Unless the solution is already very close to an equilibrium, it will take many steps to find one, and each step will be spent simulating traffic flows very similar to those in the previous iteration. On the other hand, a value of ξ which is too large is potentially even worse: the solution could oscillate back and forth between two non-equilibrium states, each time overcorrecting and never settling to a stable case. The *method of successive averages* helps overcome these twin difficulties. In the method of successive averages, ξ changes according to the

iteration number. During the first iteration, $\xi = 1/2$. During the second iteration, $\xi = 1/3$. During the third, $\xi = 1/4$, and so on. In general, during iteration k, $\xi = 1/(1+k)$. In this way, ξ starts relatively large, and becomes progressively smaller. From a behavioral standpoint, initially many drivers are switching routes, while over time fewer and fewer drivers switch routes. This strategy seeks to find an equilibrium within relatively few iterations by initially taking large steps, then reducing the step size as the equilibrium is approached.

Chapter 3

Implementation

This chapter describes how the methodology presented in Chapter 2 has been implemented in a mesoscopic simulation tool. This description is made in terms of the overall control flow of the simulation program, referencing each step in the simulator with an appropriate section from the methodology. This chapter does not contain a technical description of the C source code itself; programmers interested in a guide to the source code are referred to Appendix B.

Section 3.1 describes how the simulator works at a high level, and Section 3.2 provides additional details on the three major modules: the traffic flow (cell transmission) model; the fastest route model, which identifies the route with the least travel time between any points in the network at any departure time; and the route switching model, using the method of successive averages. Section 3.3 explains how the origin-destination table is profiled across different departure times. Section 3.4 introduces the input and output file formats; all of these are plain text files which can be edited using a number of free or commercial text editors. Sections 3.5 and 3.6 respectively describe the optional graphics modules (for creating image files based on simulation results). Finally, Section 3.7 describes the Microsoft Excel interface which allows the data files to be created, the simulation to be run, and output files to be read through a familiar user interface.

3.1 Overview

The simulator can be run either from the spreadsheet interface (by clicking on the `Run` button), or from the command line, by typing

```
wydot_dta parameters.txt
```

where the actual name of the parameters file is substituted for `parameters.txt`.

Figure 3.1 shows the basic workflow for the simulator. When first run, the program initializes by reading the following data files in sequence:

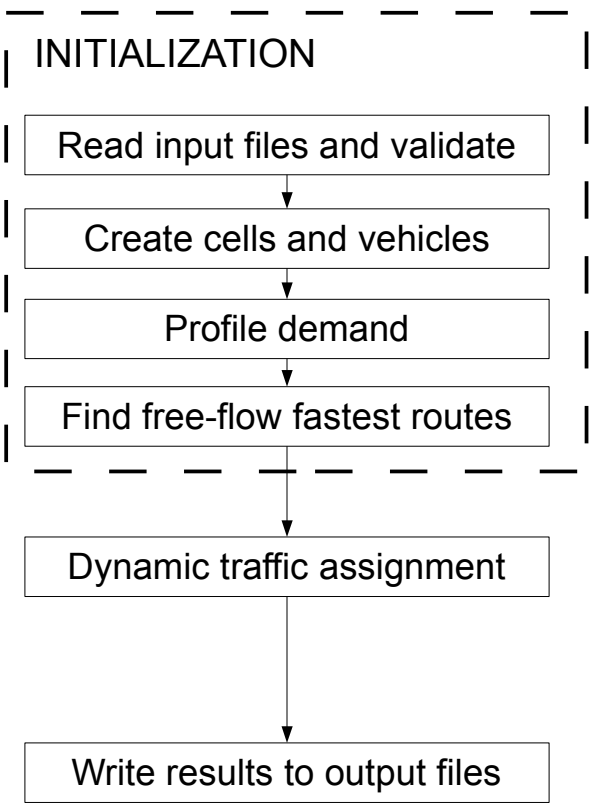


Figure 3.1: Overall simulation workflow.

1. The *parameters file*, which provides general information about the simulation run which is to be performed (such as the time step Δt and analysis period length), along with the names and locations of all the other input files.

2. The *network file*, which contains a list of every roadway link in the network and its characteristics (length, free-flow speed, etc.).

3. The *node coordinates file*, which contains a list of every intersection and its X and Y coordinates (which may be latitude and longitude, or another coordinate system).

4. The *intersection control file*, which provides detailed information on each intersection, including how it is controlled (signal, stop, etc.), which turning movements are allowed, and any additional information needed by the traffic flow model.

5. The *origin-destination (OD) matrix file*, which shows the total number of trips departing from every origin to every destination during the analysis period.

Next, the program prepares the internal structures needed for simulation: each link is divided into an appropriate number of cells, as is the list of vehicles which will eventually be assigned to the network. The OD matrix read from the input data is then profiled in a manner specified in the parameters file, converting it to a time-dependent ODT (origin-destination-departure time) array.

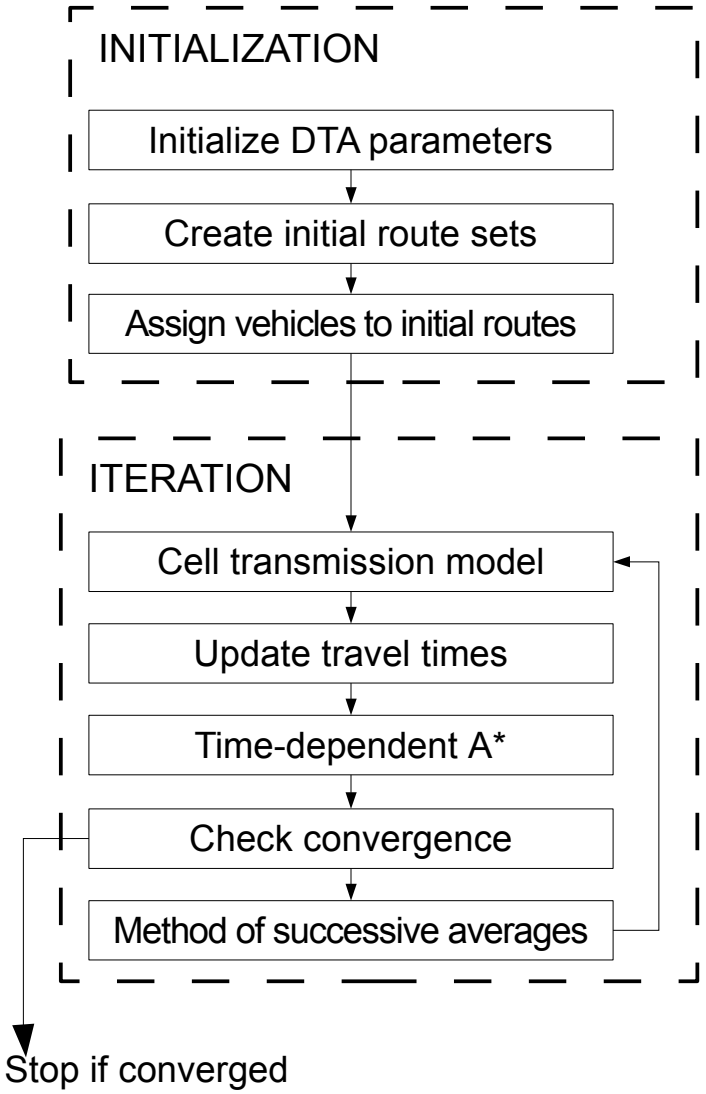


Figure 3.2: Dynamic traffic assignment workflow.

(Section 3.3 describes this process in greater detail.) As the final initialization step, the fastest route is calculated between every intersection and every destination, assuming free-flow conditions everywhere — precomputing this allows the simulation to run faster, even when network conditions are not free-flow.

After completing initialization, control switches to the main mesoscopic simulation model (termed *dynamic traffic assignment*). This is the core analysis routine which finds a mutually consistent equilibrium solution between the traffic flow and driver behavior models. The workflow for the dynamic traffic assignment process is shown in Figure 3.2. This process includes its own initialization procedures — setting initial travel conditions to free-flow everywhere, generating the initial route sets for each ODT based on the fastest free-flow routes, and assigning vehicles to these initial paths.

The dynamic traffic assignment process then begins in earnest, iterating through three primary modules — the cell transmission model, finding the fastest routes under updated conditions, and shifting some vehicles onto these routes. Each of these modules is described in detail in Section 3.2. Two additional steps are required: (1) after the cell transmission model is run, the travel time on each route must be recalculated, and (2) after each iteration of these three steps, a convergence check is performed.

Travel times for a route are calculated by adding the travel times of the constituent roadway links and turning movements. To calculate the travel time of a roadway link, the simulator makes use of the special cumulative counts $N^{\uparrow}(t)$ and $N^{\downarrow}(t)$, which respectively give the total number of vehicles which have passed the upstream and downstream ends of a link (or turn movement) by time t. To calculate the travel time for a vehicle entering at time t, we find that vehicle's exit time by finding the least integer t' such that $N^{\downarrow}(t') \geq N^{\uparrow}(t)$, and then set the travel time to the difference between t' and t (ensuring that this value is at least equal to the free-flow travel time).

The simulator uses three different convergence criteria, any or all of which can be set in the parameters file. (If multiple convergence criteria are satisfied, the simulation terminates as soon as any of them are reached.) These are:

Maximum time: If the simulation runs longer than a pre-specified time limit, it will terminate.

Maximum iterations: If the simulation has iterated among the three primary components more than a pre-specified number of times, it will terminate.

Consistency: If the simulation has achieved a certain consistency level between the traffic flow and user behavior models, it will terminate.

The first two are self-explanatory, while consistency requires further definition. Consistency is best measured against the equilibrium principle itself: at a perfectly consistent solution, all drivers are using the fastest routes available to them. So, if the solution is not perfectly consistent, one can measure the degree of consistency by comparing drivers' *actual* travel times to the travel times on the *fastest* routes they could choose from. This simulator measures this using the *average excess cost*, a metric defined in (Boyce et al., 2004) as the average difference between these values, across all vehicles.

3.2 Primary Modules

The three major modules are: (a) the traffic flow (cell transmission) model; (b) the fastest route model, which identifies the route with the least travel time between any points in the network at any departure time; and (c) the route switching model, using the method of successive averages. This section describes each of them in turn.

3.2.1 Cell transmission model

Sections 2.2.3–2.2.5 provided the mathematical formulation of the cell transmission model, link propagation, and intersection propagation models. By contrast, this section shows how these mathematical components are implemented in a computer model.

The following steps are performed in sequence, as shown in Figure 3.3:

1. Initially locate all vehicles on an artificial "origin" cell.
2. Start simulating at the initial time interval $t = 0$.
3. Identify vehicles departing at time interval t, and move them from the origin cell onto the first cell in their paths.
4. Calculate each link's sending and receiving flow at time t.
5. Move vehicles within link cells using the procedure in Section 2.2.4.
6. Process each intersection using the procedure in Section 2.2.5, moving vehicles into and out of turning movement cells.
7. If this is the last time interval, stop; otherwise increment t and return to step 2.

Although the same general procedure is used to process each intersection, there are several distinct intersection types which differ in how the target delay and capacity for each turning movement are calculated. These intersection types are as follows: internal, diverge, merge, four-way stop, two-way stop, signal, and interchange. Each is described as follows:

Internal: Internal intersections only have one upstream and one downstream link, are thus are not "true" intersections. However, they can be used to divide one roadway link into two, as in Figure 3.4. This may be useful to model a lane drop or other change in a link which does not occur at an intersection — each roadway link must be homogeneous in terms of capacity and jam density, so internal nodes can be used to mark internal points. Additional information is calculated at intersections, and so internal intersections can be inserted wherever this information would be needed. Internal intersections only have a single turning movement, with zero target delay, and their capacity is not binding[1].

Diverge: A diverge has one upstream link and multiple downstream links. Diverge turning movements have zero target delay and their capacity is not binding.

Merge: A merge has one downstream link and multiple upstream links. Diverge turning movements have zero target delay and their capacity is not binding.

[1] That is, flow can be restricted either by the capacity of the upstream or downstream links, but the turn movement does not impose any further restrictions

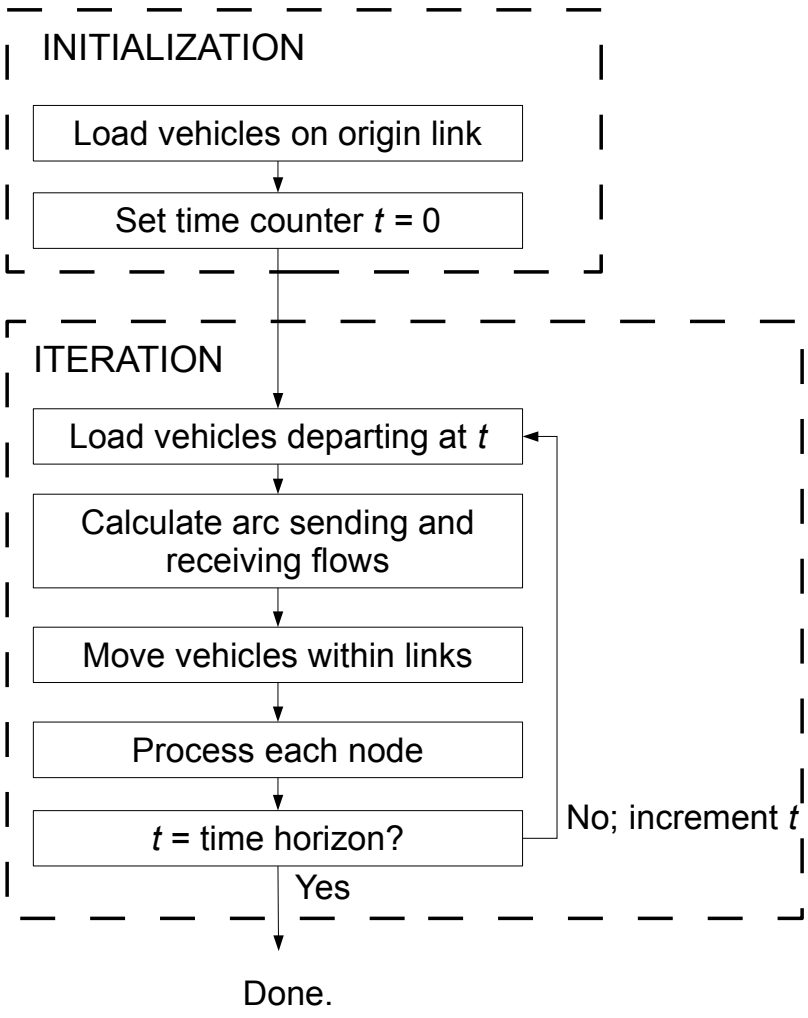


Figure 3.3: Cell transmission model workflow.

Four-way stop: Four-way stops can have multiple upstream and downstream links. They have a target delay specified as a simulation parameter (the default value is four seconds, representing time lost due to deceleration and stopping, not time spent in queue), and the capacity is specified in the intersection control file.

Two-way stop: For a two-way stop, each turn movement has two pieces of information stored with it: a saturation flow, and a priority value, indicating its relative priority in the intersection. Priority 1 movements do not need to yield to any other movement (for instance, through and right turns on the major approaches). Priority 2 movements only need to yield to Priority 1 movements (typically left turns on the major approaches); Priority 3 movements need to yield to Priority 1 and 2 movements (such as right turns on the minor approach), and so forth. Additionally, the "minimum stop priority" and "intersection capacity" must be specified. The minimum stop priority is the lowest priority movement which has a stop sign. Lower priority movements have zero target delay, while higher priority movements have the same target delay as the four way stop. When this intersection is processed, vehicles begin moving from the Priority 1 movements. If there is intersection capacity remaining, vehicles from Priority 2 movements can enter the intersection, and so on. Once the intersection capacity is exhausted, no more vehicles can move during this time interval.

Signal: For a signalized intersection, each turn movement has two pieces of information stored with it: a saturation flow, and an effective green value. Furthermore, the cycle length must be specified in the intersection control file. Target delays are calculated using the uniform delay formula in the Highway Capacity Manual (Transportation Research Board, 2010):

$$d = \frac{C}{2}\left(\frac{(1 - G/C)^2}{1 - \min\{X, 1\}G/C}\right) \tag{3.1}$$

where G is the effective green, C is the cycle length, and X is the degree of saturation (number of vehicles in the turning movement cell divided by the saturation flow and proportion of green time). No incremental delay component is needed because the dynamic traffic simulation accounts for fluctuations in arrival rate during the analysis period.

Interchange: An interchange has zero target delay for any of the turning movements, which are assumed to be grade separated. Capacities can still be specified in the intersection control file.

3.2.2 Fastest route model

Each ODT has a set of "working routes" that its vehicles are assigned to. Initially, this set only consists of the fastest route under free-flow conditions. At each iteration, the simulator finds the new fastest route for this ODT, accounting for updated travel conditions. This route is then added to the set of working routes (unless it was already there, in which case the set of working routes remains unchanged).

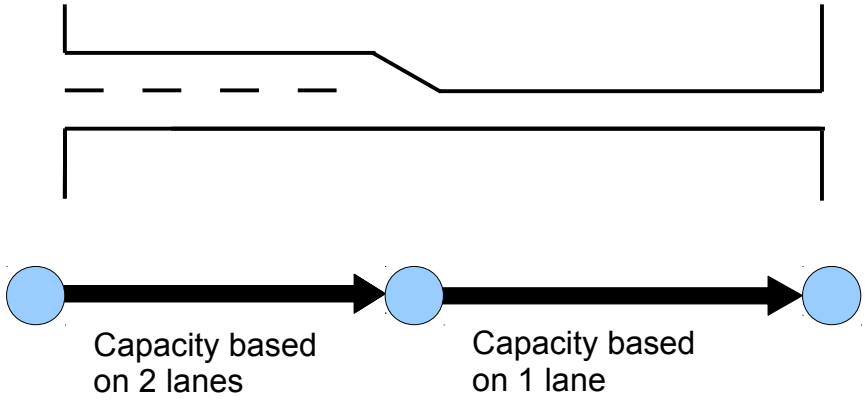


Figure 3.4: Dividing a link with a nonhomogeneous intersection.

To find these fastest routes, the simulator uses a time-dependent version of the A* shortest path algorithm, which was first developed by Hart et al. (1968) as a faster version of Dijkstra's classical shortest path algorithm. Intuitively, Dijkstra's algorithm searches in all directions from the origin r until the destination s is found, while A* uses a more directed search towards the destination. This directed search relies on having a lower bound on the travel time between any intersection and the destination. An efficient choice for this lower bound is the free-flow travel time between that intersection and the destination, which was calculated in one of the initialization steps.

This method proceeds using the following steps, and two additional data structures: a binary heap $\mathcal{H}$ of intersections to scan, and a set $\mathcal{C}$ of intersections for which the fastest route from r has already been found.

1. Initialize $\mathcal{H}$ by inserting r, and give it a label of zero.
2. Let i be the intersection in $\mathcal{H}$ with the least label; remove it from $\mathcal{H}$.
3. Scan i by performing the following steps for each intersection j directly connected to i by a single roadway link:
   (a) Calculate a temporary label $temp$ by adding (a) the travel time on the fastest route from r to i; (b) the travel time from i to j; and (c) the free-flow travel time from j to s. (Figure 3.5)
   (b) If j is not in $\mathcal{H}$, insert it into $\mathcal{H}$ with the label $temp$.
   (c) If j is already in $\mathcal{H}$ but its label is greater than $temp$, update the label of j to $temp$.
4. Add i to $\mathcal{C}$
5. If $\mathcal{H}$ is empty or s was just added to $\mathcal{C}$, end. Otherwise, return to step 2.

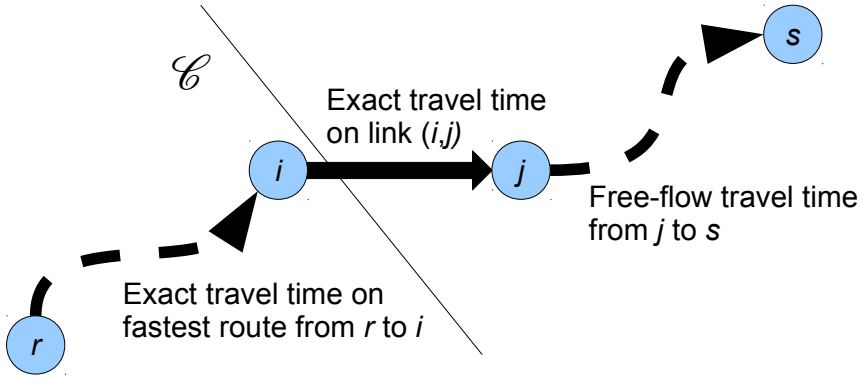


Figure 3.5: Label calculation in time-dependent A*.

3.2.3 Route switching model

As stated in Section 2.3, the method of successive averages moves a fraction of vehicles from their current paths onto the fastest path identified by the time-dependent A* algorithm. However, the total number of vehicles in an ODT can be somewhat small, and this fractional limit can be binding. For instance, at the fourth iteration, 1/5 of the vehicles should be moved onto the new fastest path. If there are only 3 vehicles corresponding to this ODT, it is unclear how this move should be performed. Therefore, the simulator uses a stochastic formula. Each vehicle moves to its ODT's fastest route with a probability of ξ, with ξ given by the formulas in Section 2.3, independent of any other vehicle's move.

3.3 Demand Profiling

Demand profiling is the process of converting a "static" or aggregate OD matrix into a time-dependent ODT array. That is, for every origin and destination r and s, we seek time-dependent departure rates $d^{rs}(t)$ such that $\sum_t d^{rs}(t) = d^{rs}$. One important simulator parameter is t_L, the time at which the last vehicle enters the network. After t_L, no additional vehicles are loaded, but the simulator completes the trips of any vehicles which have been loaded in earlier time intervals.

The simulator can profile demand automatically, using two predefined "shapes" specified in the parameters file. The predefined shapes are as follows:

Uniform: This is the simplest profile; demand is distributed evenly between the start of simulation and t_L; there is no peak, rise, or fall in the demand.

Triangle: This forms a "triangular" profile that can represent increasing, decreasing, or peaking behavior. The triangle profile consists of two linear pieces, and requires three parameters

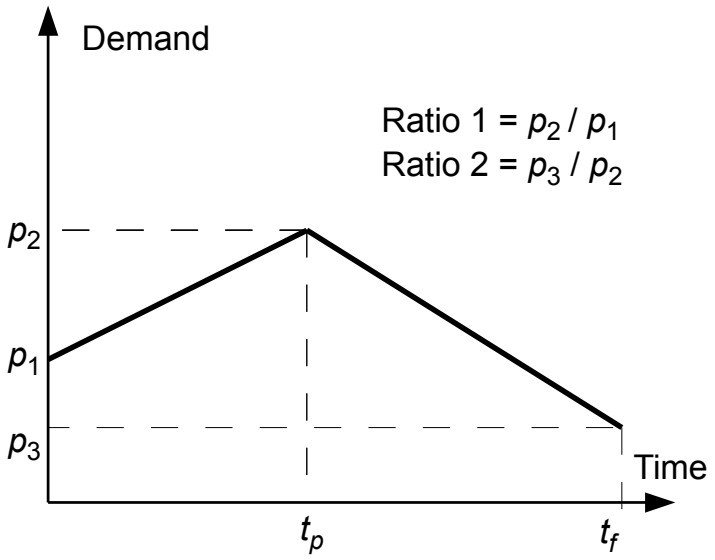


Figure 3.6: Parameter values for triangle profile.

(Figure 3.6): the *peak time* t_p; the *first ratio* R_1, and the *second ratio* R_2. The slope switches from the initial slope to the terminal slope at the peak time. Furthermore, the ratio of the demand during the peak interval during the demand at the first interval is given by R_1, and the ratio between the demand during the peak interval and the final loading interval t_f is given by R_2. This profile is flexible: by specifying a peak time of either 0 or t_f, a linear profile can be created with slope given by R_2 or R_1, respectively.

Alternatively, a "raw ODT" file can be specified which lists ODTs and flow rates explicitly. This option is more data-intensive, but can produce more reliable results if a precomputed profile is already available (perhaps from an activity-based or departure-time model).

3.4 File Formats

This section documents the formats for each input and output file used by the simulator. All of these files are plain text files to maximize ease of editing and portability. While plain text files require more disk space than binary formats, all of these files are amenable to compression and can be greatly reduced in size when not in use.

Many of these files use a standard metadata format; for instance, a typical line in the parameters file is

```
<NETWORK FILE NAME>  my_network.txt
```

The text enclosed in angle brackets is the *metadata tag* (in this case, NETWORK FILE NAME), and the remainder of the line is the *metadata value* (my_network.txt). The metadata tag is case insensitive, but the metadata value is case sensitive. All whitespace between the metadata tag and metadata value is stripped, but whitespace after the metadata value is retained. Metadata can be presented in any order in the files. In files which contain both metadata and other forms of data (such as the network file), the metadata must be presented first, and ended with a <END OF METADATA> tag.

A tilde (~) denotes a comment; any text after a tilde on a line is ignored.

3.4.1 Parameters file

The parameters file contains general values passed to the simulation, including the names of all of the other input and output files. The name of the parameters file is passed to the simulator as a command-line argument. This file only consists of metadata. Table 3.1 shows all of the metadata tags, noting which ones are required and which are optional, along with their functions. An example of a metadata file is as follows:

```
<NETWORK FILE>          braess.net
<DEMAND FILE>           braess.ods
<NODE COORDINATE FILE>  braess.nxy
<NODE CONTROL FILE>     braess.icf
<COUNTS FILE>           braess.sum
<TIME HORIZON>          3000
<LAST VEHICLE ON>       100
<AEC TOLERANCE>         0.1
<MAX RUN TIME>          60
<VERBOSITY LEVEL>       4
<TICK LENGTH>           10
<DEMAND PROFILE>        UNIFORM
<BACKWARD WAVE RATIO>   0.5
<RANDOM SEED>           0
```

Table 3.1: Metadata fields for the parameters file.

Metadata tag	Required?	Function
NETWORK FILE	Yes	Provides the name (and optional path) to the network file
DEMAND FILE	Yes	Provides the name (and optional path) to the OD matrix file, or to the raw ODT file if the demand profile is RAW
NODE COORDINATE FILE	Yes	Provides the name (and optional path) to the node coordinate file
NODE CONTROL FILE	Yes	Provides the name (and optional path) to the file containing intersection data

Continued on next page.

Metadata fields for the parameters file (continued)

Metadata tag	Required?	Function
COUNTS FILE	No	Provides the name (and optional path) for the file where complete link and turning movement cumulative counts will be reported. (This field can also be referenced with the SUMMARY FILE metadata tag, but this usage is not recommended.)
LINK SUMMARY FILE	No	Provides the name (and optional path) for the file where summary information for each link will be recorded.
NODE SUMMARY FILE	No	Provides the name (and optional path) for the file where summary information for each turning movement will be recorded.
TIME HORIZON	Yes	Provides the duration of time which will be simulated, in seconds.
TICK LENGTH	No	Provides the length of the simulation time step Δt, in seconds. If not provided, will default to 6 seconds.
LAST VEHICLE ON	Yes	Provides the time t_f at which the last vehicle will be loaded, in seconds.
WARM UP PERIOD	No	Provides the duration of the warm-up period, in seconds from the start of simulation; results in this period will not be counted in the link or node summary files. (This field is required if either a link or node summary file is present).
COOL DOWN PERIOD	No	Provides the duration of the cool-down period, in seconds before the time horizon; results in this period will not be counted in the link or node summary files. (This field is required if either a link or node summary file is present).
AEC TOLERANCE	No†	Average excess cost which will be used to declare the simulation sufficiently consistent (Section 3.1).
MAX RUN TIME	No†	Maximum run time before the simulation terminates, in seconds (Section 3.1).
MAX ITERATIONS	No†	Maximum number of dynamic traffic assignment iterations before the simulation terminates (Section 3.1).
DEMAND MULTIPLIER	No	Allows the user to scale all travel demand levels by the factor specified here. Useful for sensitivity analyses.
VERBOSITY LEVEL	No	Controls the amount of on-screen notifications provided by specifying an integer from 0 (nothing) to 5 (complete logging). The default verbosity level is 3. **Warning:** Specifying a verbosity level of 4 or 5 will create a number of additional log files. These files may be very large (over 1 GB) and greatly slow the simulation. A verbosity level of 3 or lower is recommended.

Continued on next page.

Metadata fields for the parameters file (continued)

Metadata tag	Required?	Function
VEHICLE LENGTH	No	Average effective length of a vehicle, in feet. Default value is 20 ft.
BACKWARD WAVE RATIO	No	The ratio δ between the backward and forward wave speeds (Section 3.2.1). Default value is 0.5.
RANDOM SEED	No	Provides a seed value for the random number generator, useful for replicating runs exactly. Default value is the current system time (which will generally produce slightly different results at each run).
DEMAND PROFILE	Yes	Either UNIFORM, TRIANGLE, or RAW. (Section 3.3)
PEAK DEMAND TIME	No	The peak time t_p for triangle profiles (Section 3.3). Required if the demand profile is TRIANGLE
RATIO 1	No	The first ratio R_1 for triangle profiles (Section 3.3). Required if the demand profile is TRIANGLE
RATIO 2	No	The second ratio R_2 for triangle profiles (Section 3.3). Required if the demand profile is TRIANGLE

† At least one of the three convergence criteria must be specified, or the simulator will run forever.

3.4.2 Network file

The network file consists of two components: a set of metadata fields which describe the size of the network (number of links, intersections, and zones), followed by a list of records, one per roadway link, specifying its parameters. Table 3.2 describes these metadata fields. A sample network file looks like this:

```
<NUMBER OF ZONES>    2
<NUMBER OF NODES>    6
<NUMBER OF LINKS>    7
<END OF METADATA>

~ Init node Term node Capacity Length (ft) u_f (mph) k_j(veh/mi);
   1         3         500      1500         30        200         ;
   3         4         50       1500         30        200         ;
   3         5         50       1500         30        200         ;
   4         5         50       1500         30        200         ;
   4         6         50       1500         30        200         ;
   5         6         50       1500         30        200         ;
   6         2         50       1500         30        200         ;
```

Following the metadata section, each roadway link record consists of one line of text, with six numbers and a semicolon, all separated by whitespace. These six numbers indicate (1) the

Table 3.2: Metadata fields for the network file.

Metadata tag	Required?	Function
NUMBER OF NODES	Yes	Number of intersections in the network
NUMBER OF LINKS	Yes	Number of roadway links in the network
NUMBER OF ZONES	Yes	Number of origin and destination centroids

intersection where the link starts; (2) the intersection where the link ends; (3) the capacity of the roadway link, in vehicles per hour; (4) the length of the link, in feet; (5) the free-flow speed u_f on the link, in miles per hour; and (6) the jam density k_j in vehicles per mile. Roadway links do not have to be listed in any particular order.

The intersections are numbered from 1 to NUMBER OF NODES, and textbfcentroid intersections must be listed first. That is, intersections 1–NUMBER OF ZONES correspond to centroids, and the remaining intersections are regular ones.

3.4.3 Node coordinate file

The node coordinate file has no metadata, and contains a list of coordinates for each intersection. Each intersection has one row, consisting of three numbers and a semicolon, all separated by whitespace. These three numbers are (1) the intersection ID; (2) . Intersections do not need to be listed in order of their ID.

```
~Node     X      Y   ;
1         0      0   ;
2         100    0   ;
3         10     0   ;
4         20     -10;
5         20     10  ;
6         30     0   ;
```

3.4.4 Demand matrix

The demand matrix file specifies the d^{rs} values, that is, the total number of vehicles departing each origin r for each destination s during the analysis period. This file contains three optional metadata (shown in Table 3.3), followed by <END OF METADATA>. Even if none of the optional metadata are used, the <END OF METADATA> line must still be included prior to the beginning of the OD matrix. This file has the following format:

```
<NUMBER OF ZONES>    2
<TOTAL OD FLOW>      100.0
```

Table 3.3: Metadata fields for the demand matrix file.

Metadata tag	Required?	Function
NUMBER OF ZONES	No	Number of origin and destination centroids. If included, it will be checked against the value in the network file for consistency. Including this optional field can be useful to catch errors when running simulations, in case the chosen OD matrix and network are not from the same simulation run.
DEMAND MULTIPLIER	No	Allows the user to scale all travel demand levels by the factor specified here. Useful for sensitivity analyses. (This will override any value provided in the parameters file.)
TOTAL OD FLOW	No	Lists the total number of vehicles to be assigned to the network. Providing this optional field can be useful for checking that the OD matrix has been correctly specified. If the simulation VERBOSITY is at least 3, it will report the TOTAL OD FLOW value compared to the actual number of vehicles shown in the OD matrix.

```
<DEMAND MULTIPLIER> 6
<END OF METADATA>

Origin   1
    1 :      0.0;     2 :     100.0;

Origin   2
    1 :      5.0;
```

The demand matrix is organized by origin; all of the vehicles leaving a particular origin X are listed in the section following `Origin X`. Each destination corresponding to that origin is listed, followed by colon, the number of vehicles, and a semicolon. So, in the example provided above, 0 vehicles are departing origin 1 for destination 1; 100 vehicles are departing origin 1 for destination 2; and 5 vehicles are departing origin 2 for destination 1. Not all destinations need to be provided; the simulator will assume a zero value for any origin-destination pairs not listed in this file. Fractional values can be used (these values can be thought of as "average" flow rates).

An alternative specification is the raw demand file, which is provided instead of the demand matrix file if the demand profile has RAW type. This file contains the following metadata fields, followed by one row for each ODT:

```
<NUMBER OF ODTS> 3
<NUMBER OF ZONES> 7
<TOTAL OD FLOW> 5000.000000
<DEMAND MULTIPLIER> 1
```

Table 3.4: Metadata fields for the raw demand file.

Metadata tag	Required?	Function
NUMBER OF ODTS	Yes	Provides the total number of ODTs (origin-destination-departure time combinations) in the network.
NUMBER OF ZONES	No	Number of origin and destination centroids. If included, it will be checked against the value in the network file for consistency. Including this optional field can be useful to catch errors when running simulations, in case the chosen OD matrix and network are not from the same simulation run.
DEMAND MULTIPLIER	No	Allows the user to scale all travel demand levels by the factor specified here. Useful for sensitivity analyses. (This will override any value provided in the parameters file.)
TOTAL OD FLOW	No	Lists the total number of vehicles to be assigned to the network. Providing this optional field can be useful for checking that the OD matrix has been correctly specified. If the simulation VERBOSITY is at least 3, it will report the TOTAL OD FLOW value compared to the actual number of vehicles shown in the OD matrix.

```
<END OF METADATA>

~ Origin Destination DepartureTime Demand
  1      5           1             100
  2      6           5             100
  3      7           10            100
```

Each row contains four numbers, separated by whitespace: the origin, the destination, the departure time, and the number of vehicles which are departing. The relevant metadata fields are specified in Table 3.4. Note that using this file would raise a warning, because the TOTAL OD FLOW metadata shows 5000 vehicles, which does not match the 300 vehicles which are actually listed in the remainder of the file. This allows errors to be caught before a simulation is run.

3.4.5 Intersection control file

The intersection control file provides detailed information on each intersection, the form of traffic control there, and an explicit list of the turning movements associated with that intersection. An example of such a file is below:

```
Node 1 : CENTROID
Node 2 : CENTROID
```

```
Node 3 : DIVERGE
   1 -> 3 -> 4       9999
   1 -> 3 -> 5       9999
Node 4 : DIVERGE
   3 -> 4 -> 5       9999
   3 -> 4 -> 6       9999
Node 5 : MERGE
   3 -> 5 -> 6       9999
   4 -> 5 -> 6       9999
Node 6: MERGE
   4 -> 6 -> 2       9999
   5 -> 6 -> 2       9999
```

Each intersection is introduced as `Node X : CONTROL` where `CONTROL` is the control type for this intersection. The allowable control types are: `FOUR-WAY-STOP`, `INTERCHANGE`, `TWO-WAY-STOP`, `BASIC-SIGNAL`, `CENTROID`, `MERGE`, `DIVERGE`, tttNONHOMOGENEOUS, and `UNKNOWN`. The `UNKNOWN` control should only be used in conjunction with the warrant analysis module (Section 3.6). Following this is a list of all allowable turning movements at this intersection. Every allowable movement must be listed — any movement *not* listed will not be included in the simulation. Each turning movement is signified using the notation `X -> Y -> Z`, which reflects turning from the link connecting intersection `X` to intersection `Y`, onto the link connecting `Y` to intersection `Z`. The specific format for each node type is slightly different.

For most forms of control, the name of each turning movement is followed simply by its saturation flow in vehicles per hour. This holds true for all forms of control except for `TWO-WAY-STOP` and `BASIC-SIGNAL`. For these latter two, additional information is needed on the intersection control and on each turning movement. A sample entry for a `TWO-WAY-STOP` intersection is as follows:

```
Node 8 :  TWO-WAY-STOP
   Intersection saturation flow 4999.999809
   Minimum stop priority 3
   1 -> 8 -> 9    1  4999.999809
   1 -> 8 -> 11   1  4999.999809
   7 -> 8 -> 9    2  4999.999809
   7 -> 8 -> 11   2  4999.999809
   9 -> 8 -> 11   3  4999.999809
   11 -> 8 -> 9   3  4999.999809
```

Two pieces of intersection data are required: the `Intersection saturation flow`, giving the maximum rate at which vehicles can pass through the intersection as a whole, and the `Minimum stop priority`, the least priority movement which has to stop at the sign. For each listed movement, two pieces of data are required: the stop priority corresponding to that movement, and the saturation flow.

A sample entry for a `BASIC-SIGNAL` intersection is as follows:

```
Node 11 :  BASIC-SIGNAL
   Cycle length 20
   6 -> 11 -> 5   3  4999.999809
   6 -> 11 -> 8   3  4999.999809
   6 -> 11 -> 10  3  4999.999809
   8 -> 11 -> 5   17 4999.999809
   8 -> 11 -> 6   17 4999.999809
   8 -> 11 -> 10  17 4999.999809
   10 -> 11 -> 5  17 4999.999809
   10 -> 11 -> 6  17 4999.999809
   10 -> 11 -> 8  17 4999.999809
```

Once piece of intersection data is required: the `Cycle length` for this signal. For each listed movement, two pieces of data are required: the effective green time, and the saturation flow.

3.4.6 Counts file

The counts file is an output file which reports the $N^{\uparrow}(t)$ and $N^{\downarrow}(t)$ cumulative count values and travel times for each roadway link and turning movement at all times t. **This file can be very large, and is not intended to be read directly.** Instead, this file stores all of the simulation results which will be used later, either as summarized information in the node and link summary files (Sections 3.4.8 and 3.4.7), to generate graphics, or to perform a warrant analysis.

The first half of the file reports cumulative counts and travel times for each link, and the second half reports cumulative counts and travel times for each turning movement. This information is presented in tabular form, with rows corresponding to a particular time interval and columns corresponding to roadway links (in the order given in the network file). An excerpt of such a file is shown below:

```
LINK CUMULATIVE COUNTS
----------------------
t   (1,3) Downstream  Time   (3,4) Downstream  Time   ...
10  2     0            50    0     0           40     ...
20  4     0            60    0     0           40     ...
30  6     0            70    0     0           40     ...
...
2990 343 295           3010  0     0           3010   ...
3000 344 296           3010  0     0           3010   ...

TURN MOVEMENT CUMULATIVE COUNTS
-------------------------------
t   1->3->5  Downstream  Time  1->3->4  Downstream  Time  ...
10  0        0           0     0        0           0     ...
20  0        0           0     0        0           0     ...
...
```

Note that links are indicated by their upstream and downstream intersections (so `(1,3))` is the link connecting intersection 1 to intersection 3, in that direction), and that turning movements are indicated by three intersections (`1 -> 3 -> 5` is the turning movement from link `(1,3)` to link `3,5`). There are three columns corresponding to each link or turning movement: the first shows the upstream count, the second the downstream count, and the third the travel time for vehicles entering at the time corresponding to that row (which is shown in the very first column labeled `t`).

3.4.7 Link summary file

This output file summarizes the simulation results for each roadway link, in the order given in the network file. For each link, the average travel time is reported in seconds, along with the average delay in seconds (that is, the travel time in excess of the free-flow time), along with the average density (in vehicles per mile), the average volume (in vehicles per hour) and the peak-hour factor. These can be used as input for an operational analysis, such as that in the Highway Capacity Manual. An excerpt of this file is shown below:

```
LINK SUMMARY (ALL VALUES TIME AVERAGES)
---------------------------------------
Link  Travel time (s)   Delay (s)   Density (veh/mi)  Volume (veh/hr)   PHF
(1,8)    100            0           13                86                0.53
(2,18)   346            246         66                89                0.62
(3,28)   565            465         91                89                0.76
(4,38)   575            475         86                89                0.80
(187,5)  100            0           11                73                0.47
(197,6)  100            0           8                 57                0.43
```

3.4.8 Node summary file

This output file summarizes the simulation results for each turning movement, organized by the intersection that the turning movements are associated with. For each movement, the average delay is reported (in seconds), along with the average volume (in vehicles per hour) and the peak-hour factor. These can be used as input for an operational analysis, such as that in the Highway Capacity Manual, or for signal retiming. An excerpt of this file is shown below:

```
NODE SUMMARY FILE
-----------------
   Movement          Delay (s)   Volume (vph)   PHF
Node 1 summary
   0 -> 1 -> 8       242         82             0.50
...
Node 18 summary
   108 -> 18 -> 118  0           33             0.50
```

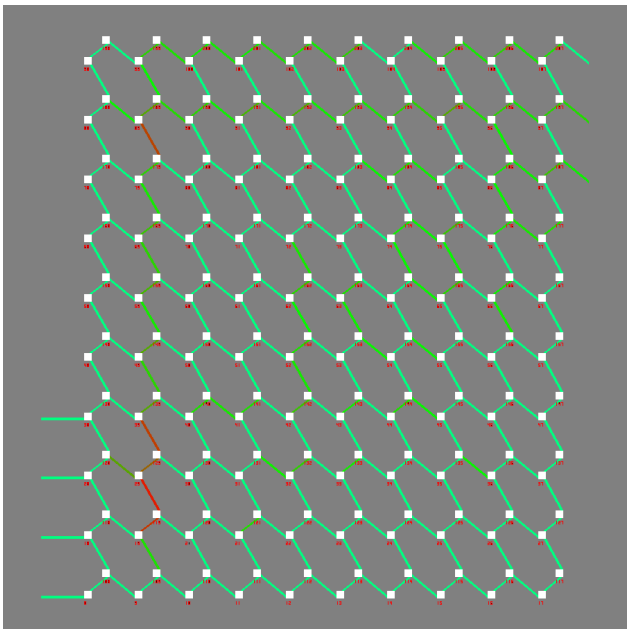


Figure 3.7: Example image for a grid network.

```
   2 -> 18 -> 118    0           89              0.62
Node 19 summary
   118 -> 19 -> 119  0           63              0.66
   109 -> 19 -> 119  0           50              0.53
Node 20 summary
   119 -> 20 -> 120  0           20              0.36
   110 -> 20 -> 120  0           4               0.25
...
```

3.5 Graphics Module

The graphics module produces image files corresponding to a simulation run, as shown in Figure 3.7. Graphics can be produced either based on the *average* level of congestion on each roadway link, or based on a *snapshot* level of congestion at each simulation tick. **These graphics files are made in the Portable Network Graphics (PNG) format, and to use this module you must have the `libpng3.dll` and `zlib.dll` libraries installed on your computer.** This format stores images in a space-efficient manner using lossless compression.

To produce graphics, the graphics module must be run separately, either from the spreadsheet or from the command line, by typing

```
wydot_graphics parameters.txt
```

where the actual name of the parameters file is substituted for `parameters.txt`. Furthermore,

Table 3.5: Metadata fields for the graphics parameters file.

Metadata tag	Required?	Function
IMAGE WIDTH	No	The width of the PNG file to create, in pixels. Default value is 500.
IMAGE HEIGHT	No	The height of the PNG file to create, in pixels. Default value is 500.
BORDER WIDTH	No	Width of the black border on all sides of the image, in pixels. Default value is 50.
NODE RADIUS	No	Each intersection is marked with a square, whose width (in pixels) is twice the value given for this metadata. Default value is 5.
LINK WIDTH	No	Each link is drawn as a straight line, whose width (in pixels) is the value given for this metadata. Default value is 2.
PNG ROOT	Yes	The start of the filename for the PNG file; the program will append `final.png` to this label.
SNAPSHOT	No	If this metadata tag is included, the code will generate a snapshot for each time interval, rather than a single "average" graphic. (Metadata value is ignored.)
EXCLUDE ZONES	No	If this metadata tag is included, the code will not plot centroid intersections or connectors. (Metadata value is ignored).

to produce graphics, the parameters file must contain the metadata `<GRAPHICS PARAMETERS FILE>`, whose corresponding metadata value is the name of the graphics parameters file, an additional text file. This file only consists of metadata; Table 3.5 gives a complete listing of the fields. An example of the graphics parameters file is as follows:

```
<IMAGE WIDTH>  800
<IMAGE HEIGHT> 800
<BORDER WIDTH> 50
<NODE RADIUS>  5
<LINK WIDTH>   3
<PNG ROOT>     gridgen2_
```

Each image uses color to depict the level of congestion on a link. Red indicates the most congested conditions, yellow indicates moderate congestion, and green indicates free-flow conditions. Continuous shading is used to reflect conditions in between. Congestion is based on the average density on each link, with jam density corresponding to red and zero density corresponding to green. This information is obtained by reading the counts file indicated in the parameters file.

3.6 Warrants Module

The warrants module uses the simulation results to determine what form of intersection control is warranted based on predicted traffic volumes. It can be used in one of two ways: (1) to generate an initial intersection control file when no data is available; and (2) as a post-processing step, to recommend an updated control scheme for re-optimizing the network based on predicted flows.

This module can only be called from the command line. The two modes of operation for this module are distinguished by the number of arguments given on the command line. For the first usage, to perform a comprehensive warrant analysis, the following command line pattern is given with four arguments:

```
wydot_warrant parametersFile networkFile initialICF finalICF
```

where `parametersFile` is the simulation parameters file, `networkFile` is the network file which will be used for executing the calibration run, `initialICF` is the file identifying which nodes will have the warrant analysis conducted, and `finalICF` is the name of the intersection control file which will include the warrant analysis. Only those intersections which are given `UNKNOWN` control in the `initialICF` file will have a warrant analysis conducted. In this case, an initial simulation is made with `INTERCHANGE` control at all nodes, determining the flow pattern if there were no delay at the nodes. These volumes are then used to perform a warrant analysis.

For the second usage, the following command line pattern is used with three arguments:

```
wydot_warrant parametersFile nodeNumber outputFile
```

where `parametersFile` is the simulation parameters file (whose `<COUNTS FILE>` has the simulation results), `nodeNumber` is the ID number for the intersection to analyze, and `outputFile` is the name of the file into which the new control data will be written.

In both cases, the warrants in the Manual for Uniform Traffic Control Devices (Federal Highway Administration, 2009) are used to classify each node's control. The first step is to identify the primary and secondary approaches to the node; this determination is made on the basis of the flow rates from the simulation counts file. Note that the primary approaches need not correspond to a through movement, but can correspond to a right or left turn (Figure 3.8). The appropriate form of signal control is then determined using tables from the Manual for Uniform Traffic Control Devices, to determine whether a signal, two-way stop, or four-way stop control is warranted. If none of these warrants are satisfied, four-way stop control is used as default.

For signalized intersections, a basic, two-phase signal timing is created using Webster's formula Webster (1958):

- Calculate the degree of saturation X_M for the major approach, based on the ratio of average volume to saturation flow.

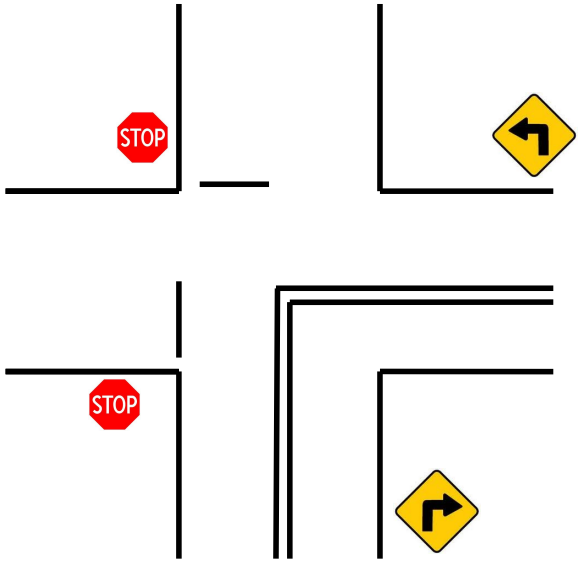


Figure 3.8: An intersection where the primary movements correspond to a turn.

- Calculate the degree of saturation X_m for the minor approach.
- Calculate the cycle length using the formula

$$C = \min\left\{\frac{5}{1 - X_M - X_m}, C_{max}\right\} \tag{3.2}$$

  where C is the calculated cycle length, and C_{max} is the maximum allowable cycle length. If $X_M + X_m \geq 1$, then $C = C_{max}$.
- Allocate green time to the major and minor approaches in proportion to X_m and X_M.

This procedure assumes no lost time, makes no saturation flow adjustments based on local conditions (such as grade or the presence of parking), and does not account for pedestrian crossing times. If this information is available, then it should be entered into the intersection control file directly, because it cannot be calculated by the warrant module.

For two-way stops, each turn movement is classified based on whether it is a right turn or left turn, and whether its upstream and downstream roadway links are major and/or minor. The node coordinates are used to determine the angle for the turning movement, and to assign the correct priority.

For four-way stops, no additional calculations are needed.

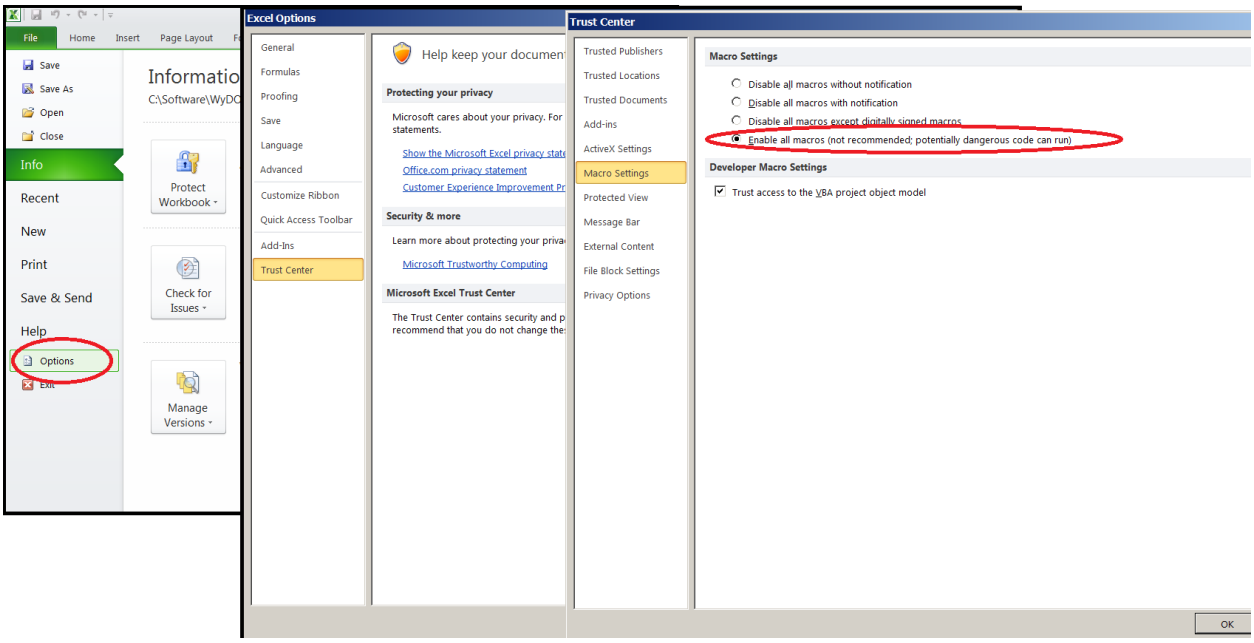


Figure 3.9: Changing macro settings in Excel.

3.7 Spreadsheet Interface

A spreadsheet interface to the simulator has been created, using Microsoft Excel and its VBA scripting language. **To use this spreadsheet, macros must be enabled in Excel.** To change the security settings to allow macros to run, click on the File tab at the upper left of the ribbon, and click "Excel Options." Click on "Trust Center" at the bottom of the left panel, then choose "Macro Settings." Select "Enable all macros." See Figure 3.9 (You should switch your macro settings back to their initial settings after you have finished using the interface, by performing the same steps and choosing a different security level.)

The interface contains a number of different worksheets. Upon first opening the interface, you will be on the Dashboard worksheet. (Figure 3.10). The buttons on this worksheet walk you through the steps of preparing the necessary input data for the simulator, running the simulator itself, and then importing the simulation summary files and graphics. You can always return to the Dashboard from any worksheet by pressing a button at the upper left.

The Project Summary worksheet is the first step in creating a new network. (Figure 3.11). On this sheet, there is room to provide information about the analysis project, as well as the engineer performing the analysis. The network data is specified below, including the number of nodes (intersections), links, and zones. Simulation parameters are listed below; these will eventually be entered into the appropriate parameters file for a simulation run. To the right is a listing of all of the input and output files which can be created by the simulator. You do not need to enter these manually; when you export the data, the VBA code will prompt you to enter the name of each file in turn. Once all of the parameters have been entered, clicking the "Prepare for manual input" button will then format the remaining sheets based on the network parameters that have been

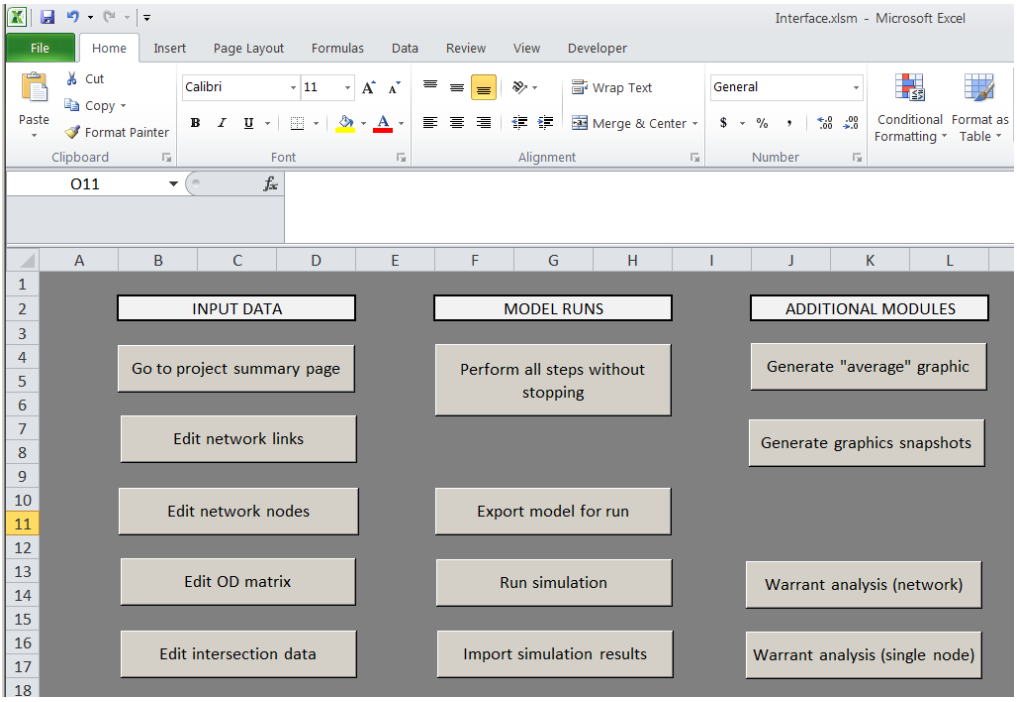


Figure 3.10: Dashboard spreadsheet.

entered.

The Link Data spreadsheet allows you to enter information for each roadway link in the network. (Figure 3.12). This file will eventually be exported to form the network file (Section 3.4.2), and each column corresponds to the descriptions in that section. Upon entering this data, click on "Proceed to node data."

The Node Data spreadsheet allows you to enter the coordinates for each intersection in the network. (Figure 3.13). This file will eventually be exported to form the node coordinates file (Section 3.4.3), and each column corresponds to the descriptions in that section. Upon entering this data, click on "Proceed to OD Matrix."

The OD Matrix spreadsheet allows you to enter the coordinates for each intersection in the network. (Figure 3.14). This file will eventually be exported to form the demand matrix file (Section 3.4.4). Upon entering this data, click on "Proceed to intersection data."

The Intersection Data spreadsheet allows you to enter information on each intersection's control type. (Figure 3.15). This spreadsheet is slightly more involved than the others. The intersection type can be selected from a drop-down box next to each node's ID. By default, the spreadsheet will allow all turning movements at an intersection, except for U-turns. The columns labeled "Forbidden movements" and "Permitted movements" allow you to override these defaults: prohibited turn movements can be entered in the "Forbidden movements" column, and if U-turns are allowed, they can be added to the "Permitted movements" column. These movements are indicated using the standard `X -> Y -> Z` notation, and a list of movements can be separated by commas in these cells. Clicking on "Edit node Y details" takes you to a secondary sheet which

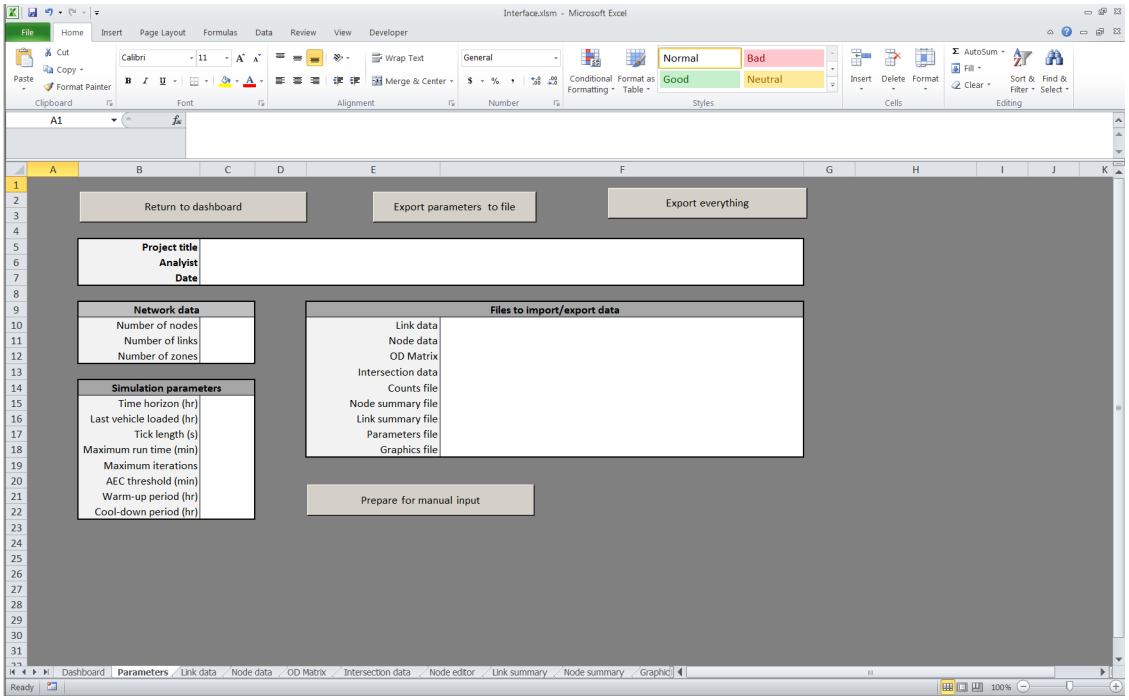
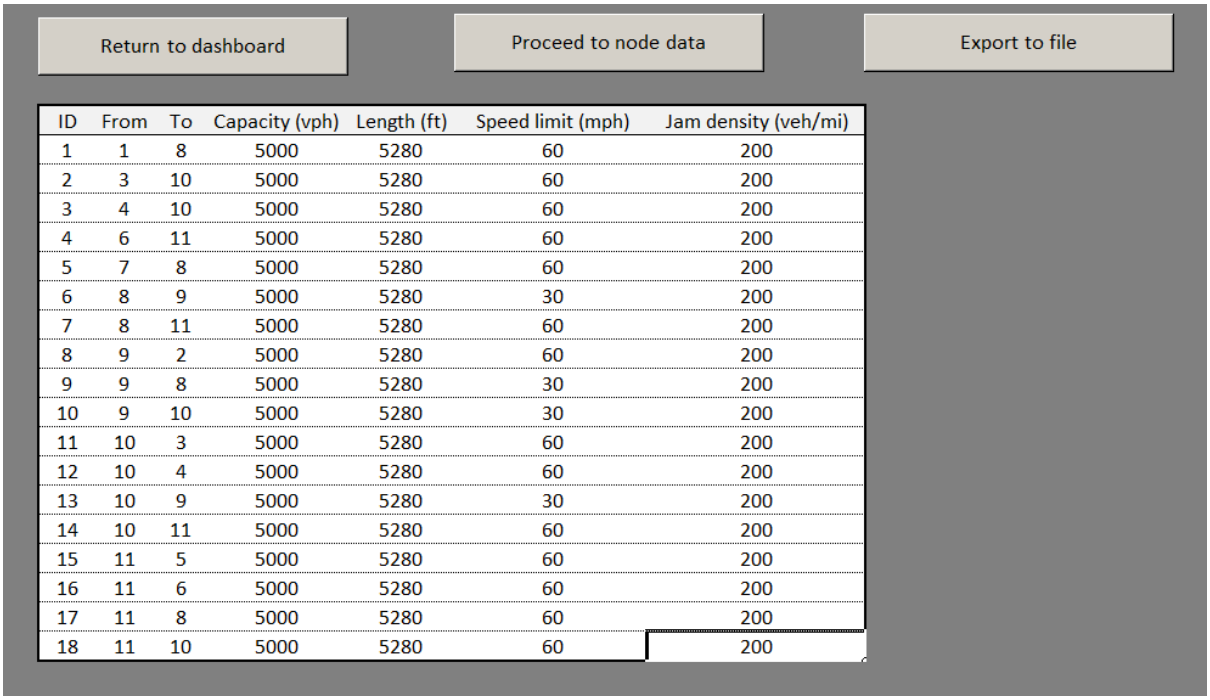
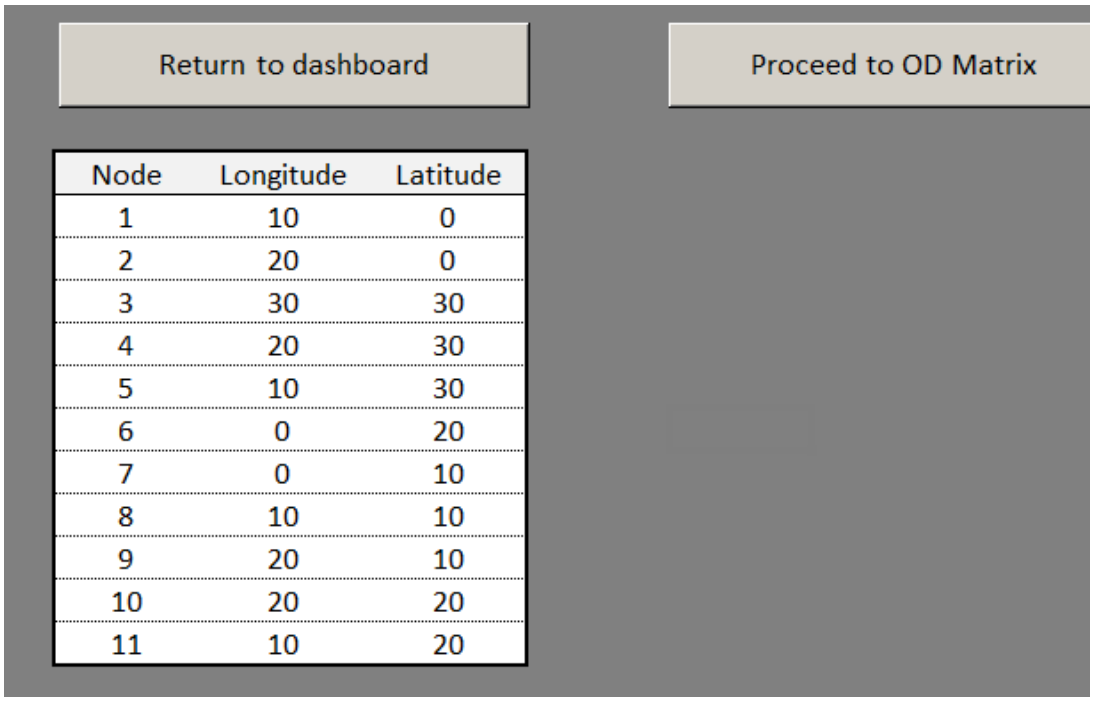


Figure 3.11: Project Summary spreadsheet.



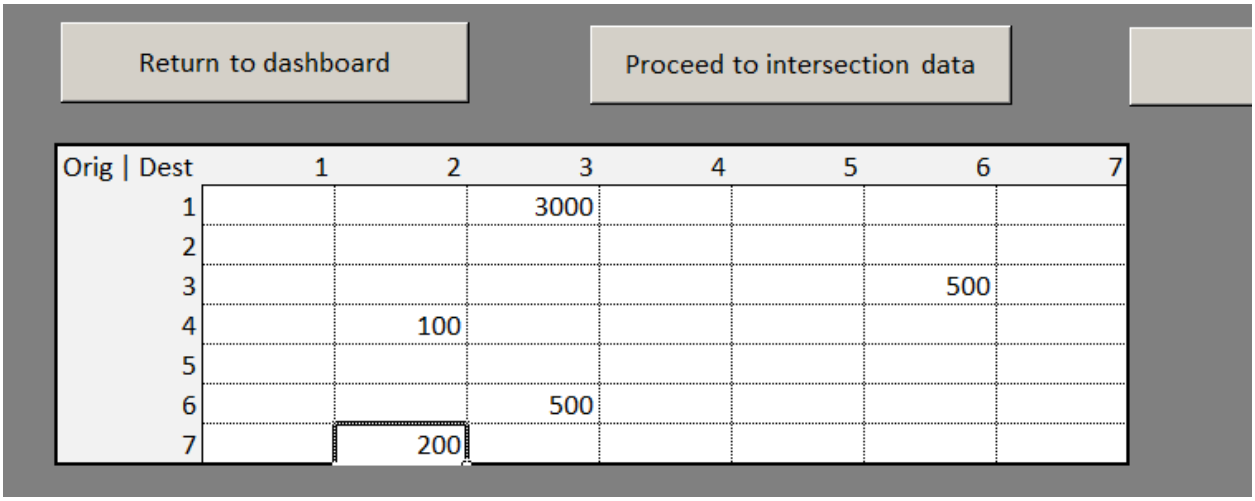
ID	From	To	Capacity (vph)	Length (ft)	Speed limit (mph)	Jam density (veh/mi)
1	1	8	5000	5280	60	200
2	3	10	5000	5280	60	200
3	4	10	5000	5280	60	200
4	6	11	5000	5280	60	200
5	7	8	5000	5280	60	200
6	8	9	5000	5280	30	200
7	8	11	5000	5280	60	200
8	9	2	5000	5280	60	200
9	9	8	5000	5280	30	200
10	9	10	5000	5280	30	200
11	10	3	5000	5280	60	200
12	10	4	5000	5280	60	200
13	10	9	5000	5280	30	200
14	10	11	5000	5280	60	200
15	11	5	5000	5280	60	200
16	11	6	5000	5280	60	200
17	11	8	5000	5280	60	200
18	11	10	5000	5280	60	200

Figure 3.12: Links spreadsheet.



Node	Longitude	Latitude
1	10	0
2	20	0
3	30	30
4	20	30
5	10	30
6	0	20
7	0	10
8	10	10
9	20	10
10	20	20
11	10	20

Figure 3.13: Node Data spreadsheet.



Orig | Dest	1	2	3	4	5	6	7
1			3000				
2							
3						500	
4		100					
5							
6			500				
7		200					

Figure 3.14: OD Matrix spreadsheet.

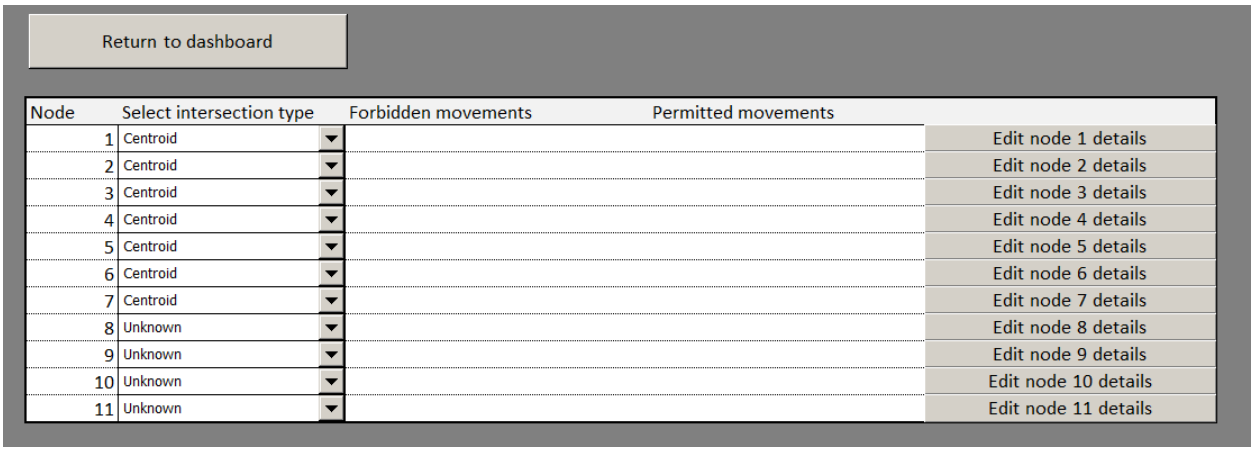
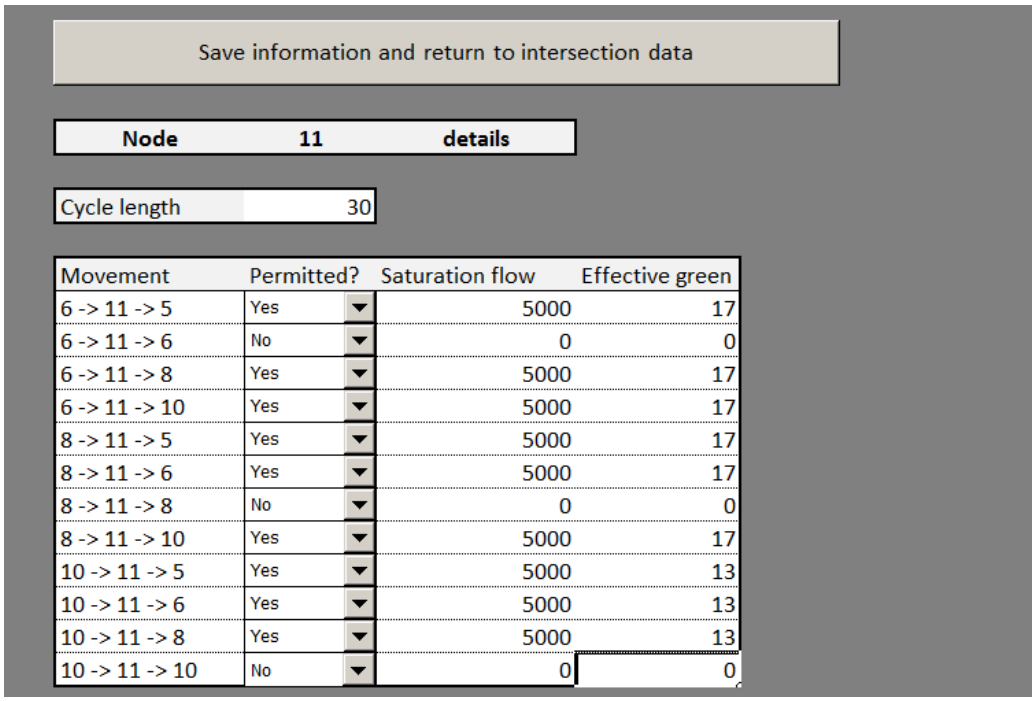


Figure 3.15: Intersection Data spreadsheet.

allows you to enter additional information on each turn movement and intersection (such as cycle lengths, movement saturation flows, green times, and priorities). (Figure 3.16). This latter sheet also allows you to toggle movements between permitted and prohibited. Upon completion of editing, you must click "Save information and return to intersection data" for this information to be properly saved.

After entering all of this data, return to the Dashboard and click "Export model for run." You will be prompted for all the names of the files to export all of the information which has been entered into the spreadsheets. At this point, you can click "Run simulation" to perform mesoscopic simulation — the program will run in the same way as if it had been called from the command line. After simulation is complete, clicking on "Import simulation results" will enter the link and intersection summary data into their respective sheets (Figures 3.18 and 3.17), along with a graphical illustration (Figure 3.19).



Save information and return to intersection data

Node	11	details

Cycle length	30

Movement	Permitted?	Saturation flow	Effective green
6 -> 11 -> 5	Yes	5000	17
6 -> 11 -> 6	No	0	0
6 -> 11 -> 8	Yes	5000	17
6 -> 11 -> 10	Yes	5000	17
8 -> 11 -> 5	Yes	5000	17
8 -> 11 -> 6	Yes	5000	17
8 -> 11 -> 8	No	0	0
8 -> 11 -> 10	Yes	5000	17
10 -> 11 -> 5	Yes	5000	13
10 -> 11 -> 6	Yes	5000	13
10 -> 11 -> 8	Yes	5000	13
10 -> 11 -> 10	No	0	0

Figure 3.16: Node Data spreadsheet.

ID	From	To	Travel time (s)	Delay (s)	Density (veh/mi)	Volume (vph)	PHF
1	1	8	60	0	25	1533	0.75
2	3	10	60	0	4	255	0.73
3	4	10	60	0	1	44	0.53
4	6	11	60	0	4	251	0.72
5	7	8	60	0	2	104	0.7
6	8	9	120	0	4	108	0.72
7	8	11	60	0	26	1571	0.77
8	9	2	60	0	3	161	0.72
9	9	8	120	0	0	0	---
10	9	10	120	0	0	0	---
11	10	3	60	0	32	1910	0.8
12	10	4	60	0	0	0	---
13	10	9	120	0	2	49	0.59
14	10	11	60	0	4	261	0.74
15	11	5	60	0	0	0	---
16	11	6	60	0	4	267	0.76
17	11	8	60	0	0	0	---
18	11	10	61	1	31	1862	0.78

Figure 3.17: Link Summary spreadsheet.

From	->	Node	->	To	Delay (s)	Volume (vph)	PHF
0	->	1	->	8	0	1499	0.74
9	->	2	->	0	0	161	0.72
10	->	3	->	0	0	1910	0.8
0	->	3	->	10	0	249	0.71
10	->	4	->	0	0	0	---
0	->	4	->	10	0	43	0.52
11	->	5	->	0	0	0	---
11	->	6	->	0	0	267	0.76
0	->	6	->	11	0	246	0.7
0	->	7	->	8	0	103	0.69
11	->	8	->	9	0	0	---
9	->	8	->	11	0	0	---

Figure 3.18: Node Summary spreadsheet.

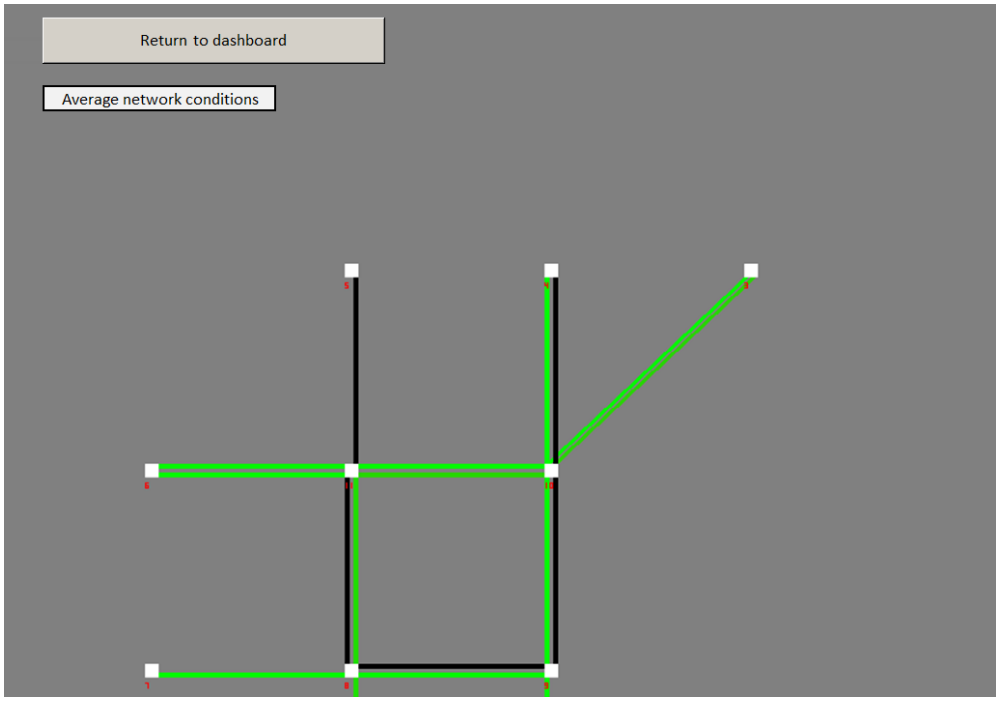


Figure 3.19: Graphics spreadsheet.

Chapter 4

Case Studies

This chapter presents three different networks as case studies for the mesoscopic simulator: a small "toy" network, the city of Casper, and the state of Wyoming. Each case study demonstrates a different aspect of the simulator and modules. The toy network is small enough for the impact of its results to be immediately apparent; this further serves as a demonstration of the warrant analysis. The Casper network represents one of Wyoming's largest cities, and demonstrates the applicability of the tool for quantifying traffic diversion due to a work zone closing a major thoroughfare. The Wyoming network represents the major freeways throughout the entire state, and forms the context for quantifying traffic diversion due to a hypothetical toll imposed on I-80.

In this chapter, the focus is mainly on the network constructions, and interpreting the result summary and graphics files. Detailed tutorials, with step-by-step instructions for performing these analysis, can be found in Appendix A.

4.1 Toy Network

Consider the network shown in Figure 4.1. Intersections 1–7 are centroids. Every link is 1 mile long and has a capacity of 5000 vph and jam density 200 veh/mi; the thick shaded links have a speed limit of 30 mph and all other links have a speed limit of 60 mph. 3000 vehicles depart from zone 1 to zone 3; 500 vehicles from zone to 3 to zone 6; 100 from zone 4 to zone 2; 500 from 6 to 3; and 200 from 7 to 2. Assume that the node controls at intersections 8, 9, 10, and 11 is currently unknown. This leads to the following incomplete intersection control file:

```
Node 1 : CENTROID
Node 2 : CENTROID
Node 3 : CENTROID
Node 4 : CENTROID
Node 5 : CENTROID
Node 6 : CENTROID
```

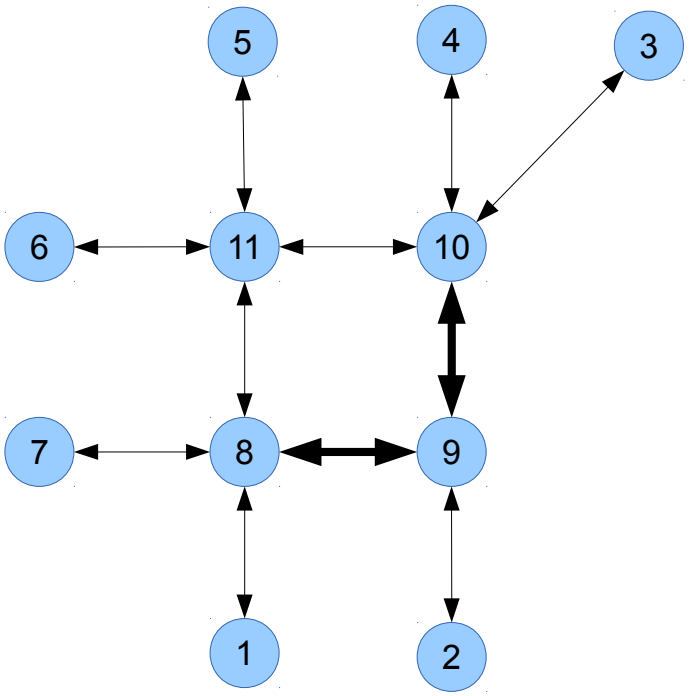


Figure 4.1: Toy network schematic.

```
Node 7 : CENTROID
Node 8 : UNKNOWN
Node 9 : UNKNOWN
Node 10 : UNKNOWN
Node 11 : UNKNOWN
```

Running the warrant analysis module, volumes are calculated on a temporary basis, assuming that each of nodes 8–11 has four-way stop control. Upon analyzing these volumes, the warrant analysis module generates the following, completed intersection control file:

```
Node 1 :  CENTROID
Node 2 :  CENTROID
Node 3 :  CENTROID
Node 4 :  CENTROID
Node 5 :  CENTROID
Node 6 :  CENTROID
Node 7 :  CENTROID
Node 8 :  TWO-WAY-STOP
   Intersection saturation flow 4999.999809
   Minimum stop priority 3
   1 -> 8 -> 9 1  4999.999809
   1 -> 8 -> 11   1  4999.999809
   7 -> 8 -> 9 2  4999.999809
```

```
   7 -> 8 -> 11   2  4999.999809
   9 -> 8 -> 11   3  4999.999809
   11 -> 8 -> 9   3  4999.999809
Node 9 :  BASIC-SIGNAL
   Cycle length 20
   8 -> 9 -> 2 10 4999.999809
   8 -> 9 -> 10   10 4999.999809
   10 -> 9 -> 2   10 4999.999809
   10 -> 9 -> 8   10 4999.999809
Node 10 :  BASIC-SIGNAL
   Cycle length 20
   3 -> 10 -> 4   16 4999.999809
   3 -> 10 -> 9   16 4999.999809
   3 -> 10 -> 11  16 4999.999809
   4 -> 10 -> 3   16 4999.999809
   4 -> 10 -> 9   16 4999.999809
   4 -> 10 -> 11  16 4999.999809
   9 -> 10 -> 3   4  4999.999809
   9 -> 10 -> 4   4  4999.999809
   9 -> 10 -> 11  4  4999.999809
   11 -> 10 -> 3  4  4999.999809
   11 -> 10 -> 4  4  4999.999809
   11 -> 10 -> 9  4  4999.999809
Node 11 :  BASIC-SIGNAL
   Cycle length 20
   6 -> 11 -> 5   15 4999.999809
   6 -> 11 -> 8   15 4999.999809
   6 -> 11 -> 10  15 4999.999809
   8 -> 11 -> 5   15 4999.999809
   8 -> 11 -> 6   15 4999.999809
   8 -> 11 -> 10  15 4999.999809
   10 -> 11 -> 5  5  4999.999809
   10 -> 11 -> 6  5  4999.999809
   10 -> 11 -> 8  5  4999.999809
```

Notice that a two-way stop is recommended at node 8, and signals at nodes 9, 10, and 11. Each signal has a short cycle length (20 seconds). At node 9, the signal time is divided between the two approaches, while nodes 10 and 11 use a less even distribution because of different approach volumes. Running the main simulator produces the following link flows:

```
LINK SUMMARY (ALL VALUES TIME AVERAGES)
---------------------------------------
Link  Time (s) Delay (s)   Density  Volume   PHF
(1,8)    60    0           39       2357     0.92
(3,10)   60    0           7        398      0.90
(4,10)   60    0           1        81       0.85
...
```

and turning movement summary:

```
NODE SUMMARY FILE
-----------------
   Movement Delay (s)   Volume (vph)   PHF
Node 1 summary
   0 -> 1 -> 8 0  2314  0.90
Node 2 summary
   9 -> 2 -> 0 0  261   0.92
Node 3 summary
   10 -> 3 -> 0   0  2894  0.96
   0 -> 3 -> 10   0  391   0.88
```

4.2 Casper

The Casper network was constructed from the TransCAD model used for long-range planning. After making the necessary conversions to mesoscopic simulation format, this network has 304 centroids, 1014 intersections, and 2760 roadway links. The entire network is shown in Figure 4.2 — in this and similar figures, the color indicates the level of congestion on a link, based on its density. Green indicates free-flow conditions, red congested conditions, and intermediate shades reflect traffic conditions in between. Black indicates links with very little flow. To simulate a work zone closure, the link representing Yellowstone Highway between Beverly St and C St is closed (represented in the simulator by deleting its link from the network file) (Figure 4.3).

Figure 4.4 shows how roadway volume has shifted before (left) and after (right) the work zone closure. For a more quantitative view, the node summary file shows how the flows around intersection 436 (Yellowstone Hwy & Beverly St) have changed, as compiled in Table 4.1. Note the substantial diversion of flow away from this intersection after the closure. This reflects travelers choosing alternate routes to avoid the work zone and closure.

4.3 Wyoming

The Wyoming network was constructed manually, including every interstate and federal highway in the State, along with several "external" intersections and links which represent diversion opportunities outside the state (Figure 4.5). More details on the construction process can be found in Saha et al. (2013). The specific policy studied here was levying a toll on I-80 between Rock Springs and Rawlins, as suggested by Wyoming Department of Transportation (2008).

While the simulator does not directly model tolls on links, a toll can be effectively modeled by adjusting the free-flow speed of a link, as follows: to simulate a $20 toll, we increase the free-flow travel time on this link by an equivalent amount. This equivalency depends on travelers' value of time; this demonstration assumes an average $10/hr value of time, a standard figure in the tolling

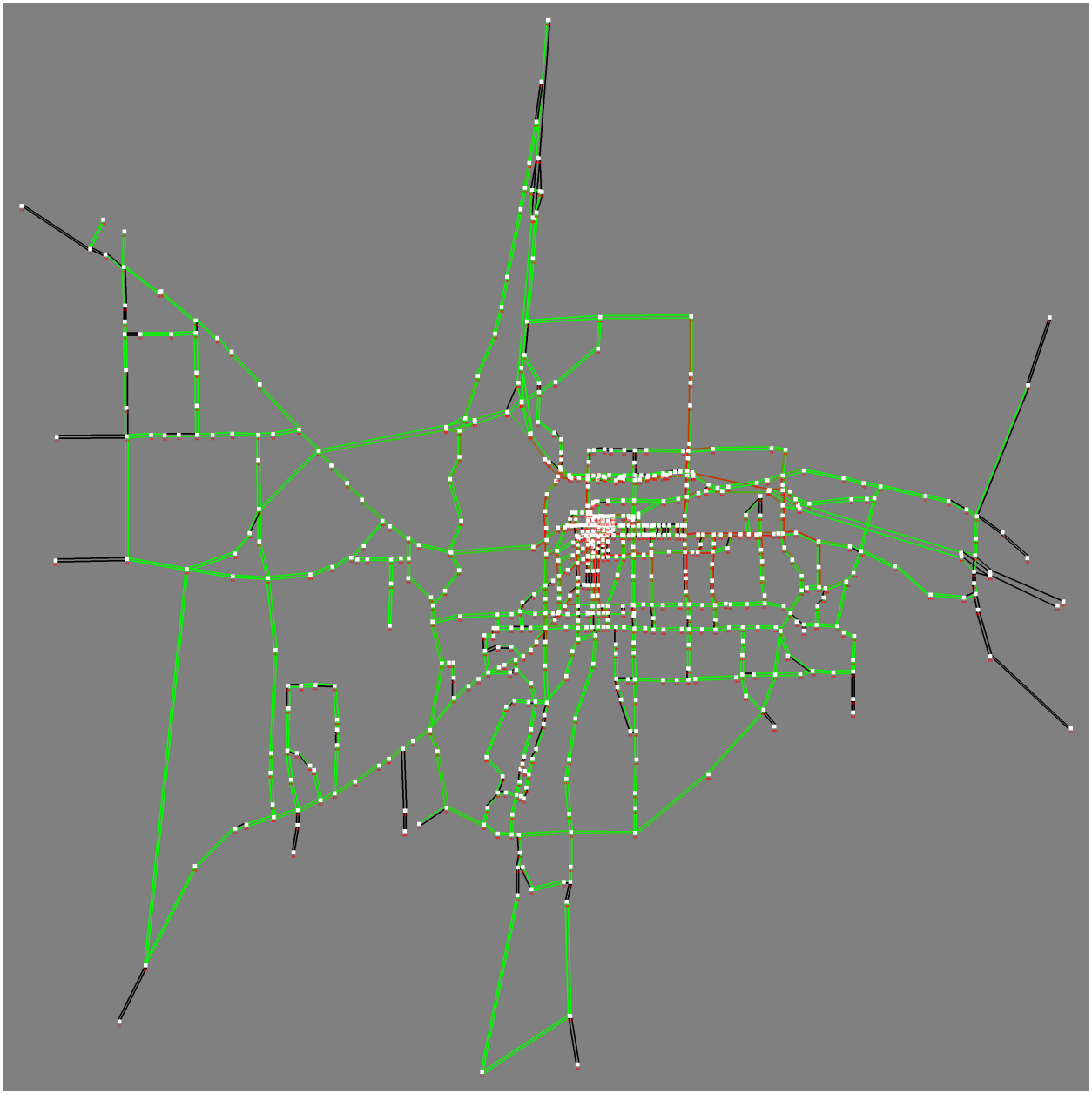


Figure 4.2: Map of the entire Casper network.

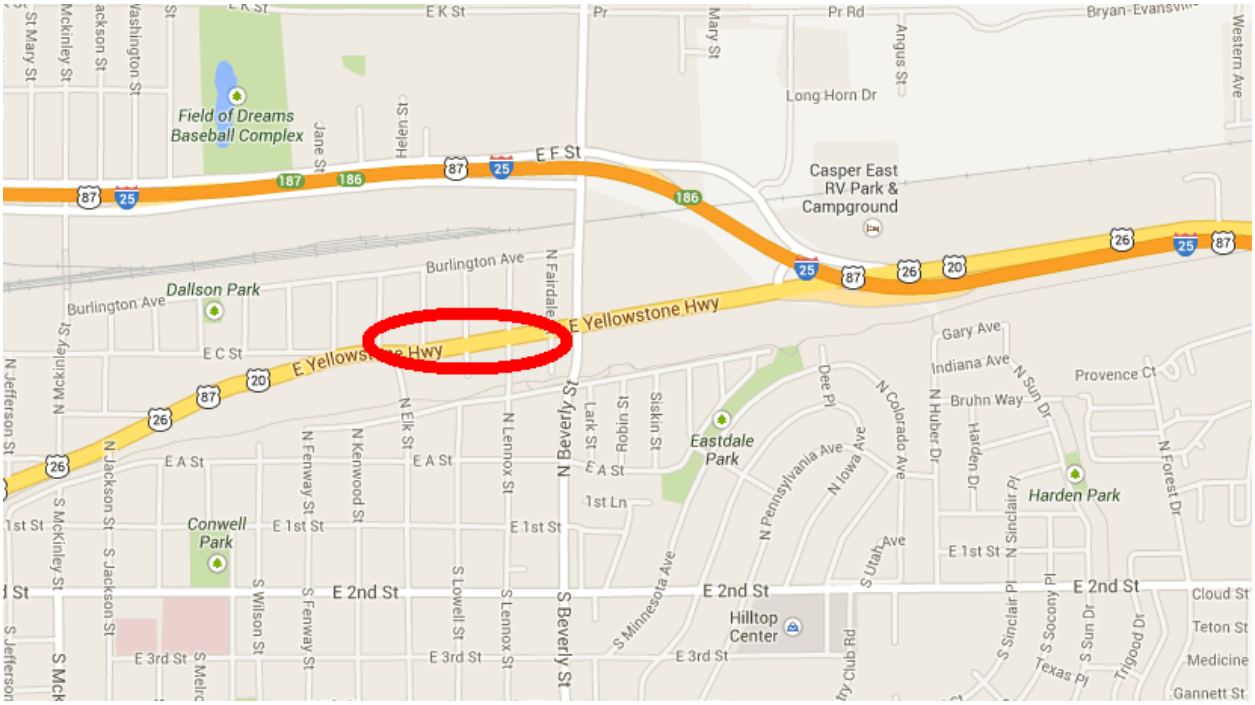


Figure 4.3: Link closed between Beverly St. & C St. for work zone.

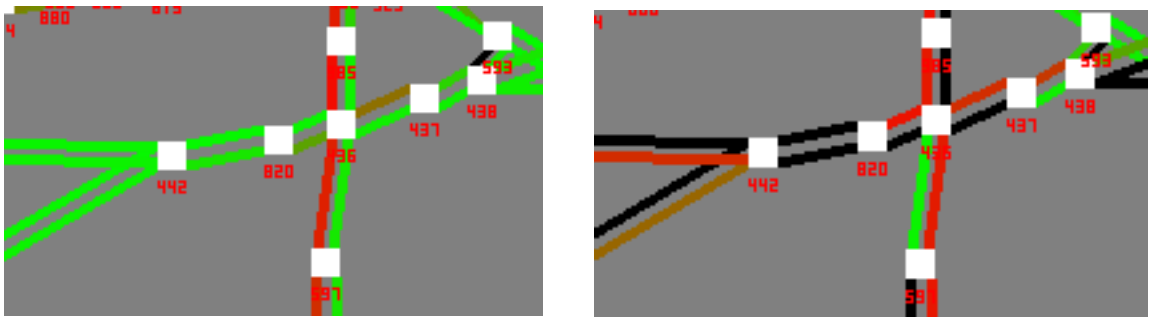


Figure 4.4: Link congestion between Beverly St. & C St. before and after work zone.

Table 4.1: Turning movement flows before and after closure of Yellowstone Hwy.

Movement	Flow before closure	Flow after closure
820 -> 436 -> 985	27	0
820 -> 436 -> 597	80	0
820 -> 436 -> 437	105	0
597 -> 436 -> 985	165	34
597 -> 436 -> 820	85	5
597 -> 436 -> 437	160	39
437 -> 436 -> 985	4	1
437 -> 436 -> 820	48	1
437 -> 436 -> 597	70	24
985 -> 436 -> 820	34	5
985 -> 436 -> 597	120	45
985 -> 436 -> 437	17	14

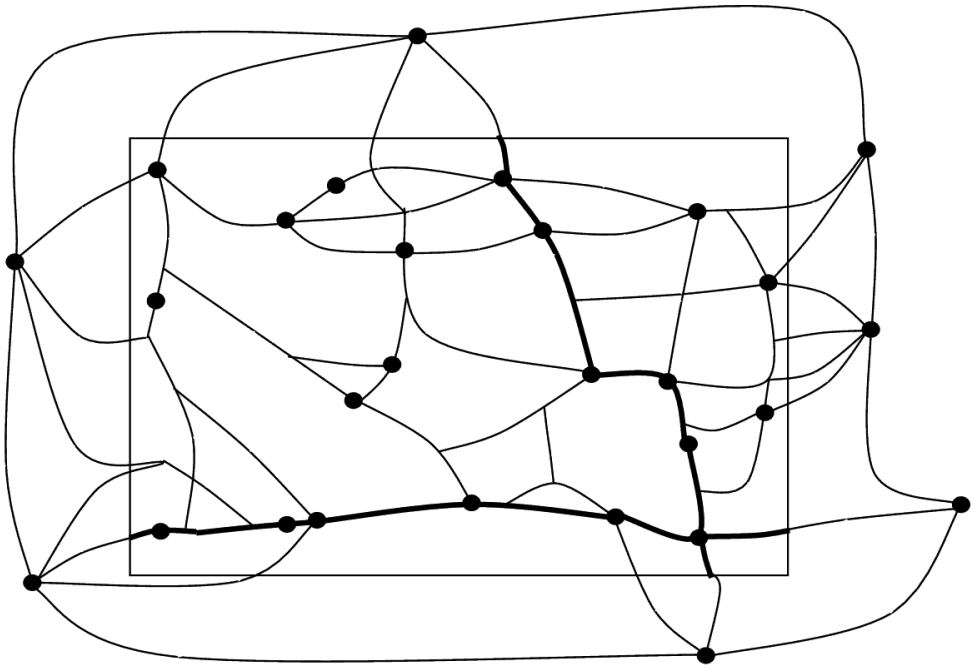


Figure 4.5: Statewide network for Wyoming.

literature. This segment is 111 miles long, and has a speed limit of 75 mph. At this speed, the link takes 1.48 hours to traverse. At $10/hr value of time, the $20 toll imposes the equivalent of two additional hours of time, or an equivalent of 3.48 hours. This, in turn, translates to a speed of 32 mph for the 111 mile distance. Therefore, in the network file, the speed limit for I-80 was reduced to 32 mph between Rock Springs and Rawlins to produce the same effect as a $20 toll.

Viewing the link summary file, we can quantify the amount of diversion: prior to imposing the toll, the average annual daily traffic (AADT) count was approximately 6650 at this location, while after the toll, the AADT count decreased to 2800. Thus, approximately 3800 vehicles diverted onto an alternate route, primarily out-of-state traffic. This new AADT count can also be used to forecast toll revenue.

Chapter 5

Summary & Conclusions

This project developed a mesoscopic simulation software capable of modeling both cities and statewide regions. The key concepts are (1) a traffic flow model, which is realistic enough to capture basic traffic dynamics, yet efficient and scalable to very large regions, and (2) a user behavior model where route choice and diversion are determined endogenously, based on simulated travel times. To this end, the cell transmission model was integrated with a user equilibrium principle to produce an efficient, dynamic traffic assignment simulator.

This simulation software was implemented in the C programming language, with a Microsoft Excel VBA frontend. The simulation itself proceeds in an iterative process, moving towards consistency between the traffic flow and user behavior models. The iteration proceeds through three primary submodules: the cell transmission model; the time-dependent A* algorithm to find the least-cost routes for each origin, destination, and departure time; and the method of successive averages to shift an appropriate number of vehicles from longer routes to shorter ones.

All input and output from the simulation takes the form of plain text files which are portable, human-readable, and easy to edit. A spreadsheet interface is also provided to facilitate data entry and analysis of results. Two additional modules were developed: a graphics module which produces network maps showing congestion patterns, and a warrant analysis module. The latter serves two purposes, and can overcome data limitations by developing a basic intersection control pattern throughout the network based on engineering warrants, or alternately serve as a postprocessing procedure to determine updated intersection control after simulation.

Case studies demonstrate this in both the Casper network, and a statewide network representing all of Wyoming. Appendices to the main document include tutorials, a programmer's guide to the source code, and the C and VBA code itself.

References

Beckmann, M. J., C. B. McGuire, and C. B. Winston (1956). *Studies in the Economics of Transportation*. New Haven, CT: Yale University Press.

Boyce, D., B. Ralevic-Dekic, and H. Bar-Gera (2004). Convergence of traffic assignments: how much is enough? *Journal of Transportation Engineering 130*(1), 49–55.

Boyles, S. D. and S. T. Waller (2010). Traffic network analysis and design. In J. J. Cochran (Ed.), *Wiley Encyclopedia of Operations Research*. Wiley.

Courant, R., K. Friedrichs, and H. Lewy (1928). Über die partiellen differenzengleichungen der mathematischen physik. *Mathematische Annalen 100*(1), 32–74.

Daganzo, C. F. (1994). The cell transmission model: a dynamic representation of highway traffic consistent with the hydrodynamic theory. *Transportation Research Part B 28*(4), 269–287.

Federal Highway Administration (2009). *Manual on Uniform Traffic Control Devices*. Washington, DC: US Department of Transportation.

Godunov, S. K. (1959). A difference scheme for numerical solution of discontinuous solution of hydrodynamic equations. *Matematicheskii Sbornik 47*, 271–306.

Hart, P. E., N. J. Nilsson, and B. Raphael (1968). A formal basis for the heuristic determination of minimum cost paths. *IEEE Transactions on Systems Science and Cybernetics SSC4 4*(2), 100–107.

Lighthill, M. and G. Whitham (1955). On kinematic waves. II. A theory of traffic flow on long crowded roads. *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences*, 317–345.

Patriksson, M. (1994). *The Traffic Assignment Problem — Models and Methods*. Utrecht, Netherlands: VSP.

Pigou, A. C. (1920). *The Economics of Welfare*. London: Macmillan and Co.

Richards, P. (1956). Shock waves on the highway. *Operations Research 4*(1), 42–51.

Saha, P., R. Liu, C. Melson, and S. D. Boyles (2013). Network model for rural roadway tolling with pavement deterioration and repair. In review, *Computer-Aided Civil and Infrastructure Engineering*.

Transportation Research Board (2010). *Highway Capacity Manual*. Washington, DC: National Research Council.

Wardrop, J. (1952). Some theoretical aspects of road traffic research. *Proceedings of the Institute of Civil Engineers, Part II*, 325–378.

Webster, F. V. (1958). Traffic signal settings. Technical report, Her Majesty's Stationery Office, London. Road Research Technical Paper No. 30.

Wyoming Department of Transportation (2008). Interstate 80 tolling feasibility study. Prepared by Parsons Brinkerhoff in association with PB Consult.

Yperman, I. (2007). *The Link Transmission Model for Dynamic Newtork Loading*. Ph. D. thesis, Katholieke Universiteit Leuven, Belgium.

Appendix A

Tutorials

This appendix contains in-depth tutorials for the three case studies in Chapter 4. These include:

1. A small toy network which is made from scratch, showing how to use the interface to create and edit data files. This example also shows how to use the warrant analysis and graphics modules as well.
2. A network representing the city of Casper. This example shows how the simulator can be used to predict the influence of a work zone closure on traffic diversion, and on re-optimizing signal control.
3. A network representing the state of Wyoming. This example shows how the simulator can reflect large-scale diversion which can occur as a result of a toll on I-80. This reflects a less conventional use of the traffic simulator and shows the flexibility of the mesoscopic approach.

Specific instructions for the tutorial are printed in **boldface**, interspersed with additional description of how the program is working.

A.1 Toy network

We want to create the network shown schematically in Figure A.1. Note that the node numberings have been determined in advance, and are chosen so that the origin and destination centroids have the lowest numbers (1–7), while the regular intersections 8–11 have the higher ID numbers. Intersections 1–7 are centroids. Every link is 1 mile long and has a capacity of 5000 vph and jam density 200 veh/mi; the thick shaded links have a speed limit of 30 mph and all other links have a speed limit of 60 mph. According to a travel demand model which has been conducted earlier, 3000 vehicles depart from zone 1 to zone 3; 500 vehicles from zone to 3 to zone 6; 100 from zone

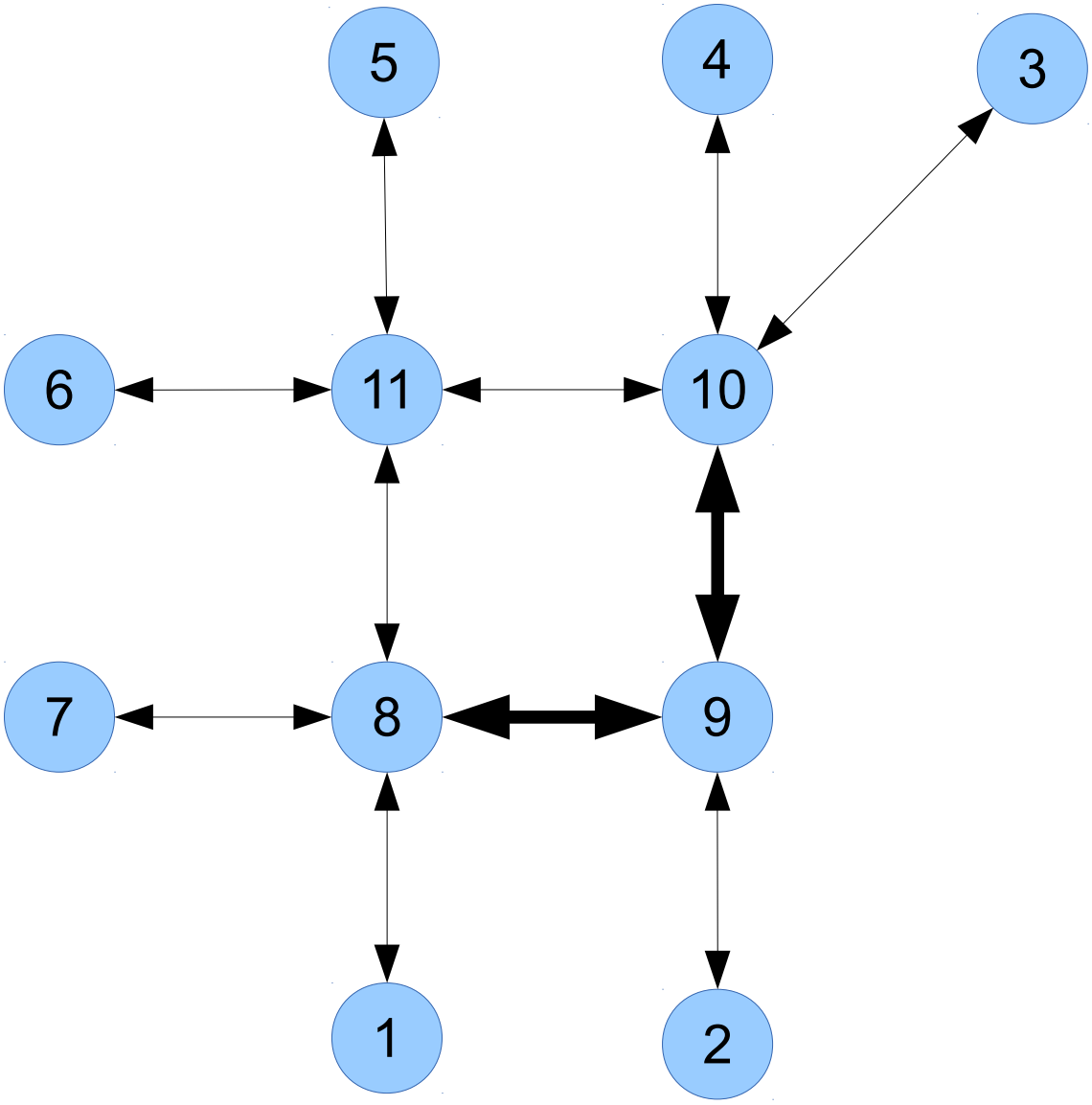


Figure A.1: Toy network for tutorial.

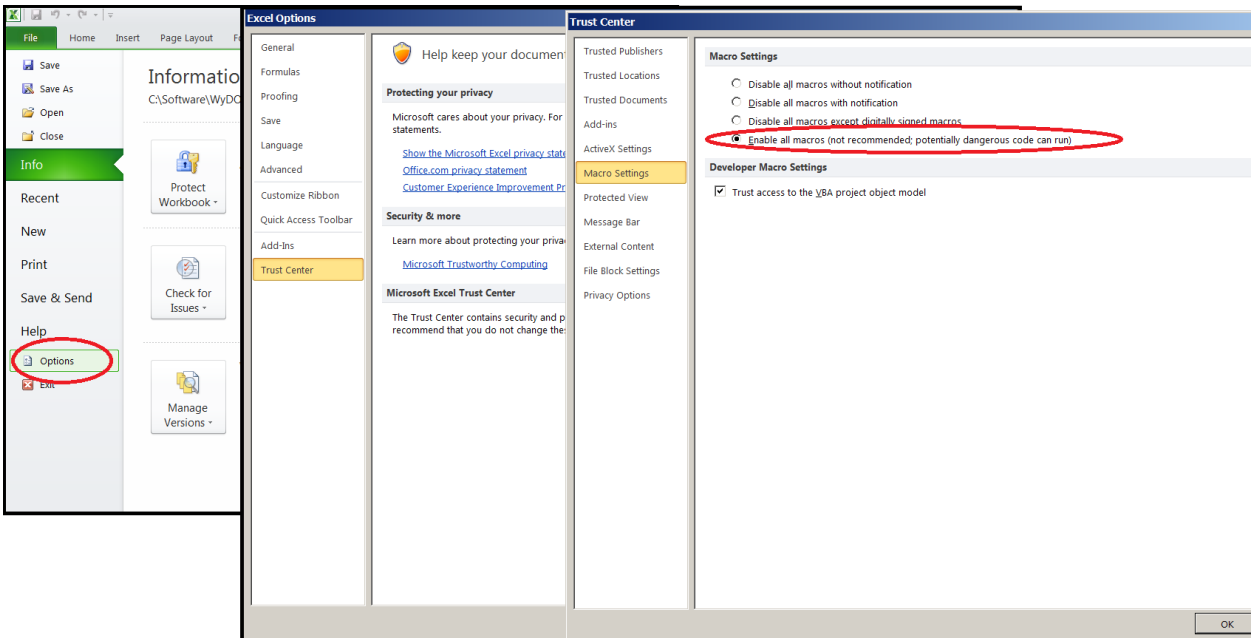


Figure A.2: Changing macro settings in Excel.

4 to zone 2; 500 from 6 to 3; and 200 from 7 to 2. Assume that the node controls at intersections 8, 9, 10, and 11 is currently unknown.

Open the spreadsheet `interface.xlsm` with Microsoft Excel. This interface relies extensively on Excel VBA macros, which must be enabled. If you receive a warning about macros being disabled because of your security settings, follow these instructions: click on the File tab at the upper left of the ribbon, and click "Excel Options." Click on "Trust Center" at the bottom of the left panel, then choose "Macro Settings." Select "Enable all macros." See Figure A.2 (You should switch your macro settings back to their initial settings after you have finished using the interface, by performing the same steps and choosing a different security level.)

You should see the dashboard shown in Figure A.3. **Click on "Go to project summary page"** underneath "Input Data." This will take you to the Parameters sheet, where you can enter in the basic project information the interface needs to construct the remainder of the sheets. (Figure A.4). **Enter in the following information in the cells marked "Network data" and "Simulation parameters":**

Number of nodes: 11

Number of links: 18

Number of zones: 7

Time horizon (hr): 2

Last vehicle loaded (hr): 1

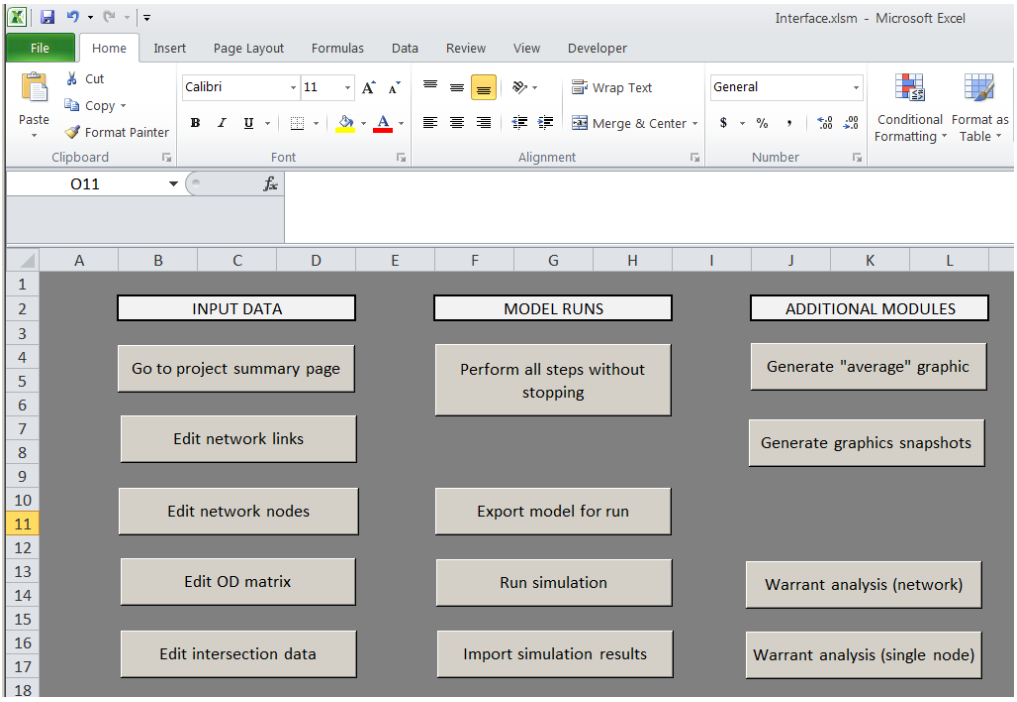


Figure A.3: Dashboard screenshot.

Tick length (s): 10

Maximum run time (min): 10

AEC threshold (min): 5

Warm-up period (hr): 0.25

Cool-down period (hr): 0.25

For more details on what each of these parameters does, consult the relevant sections in Chapter 3. After entering this information, the spreadsheet should appear as in Figure A.5.

Now, **press the "Prepare for manual input" button at the bottom of the sheet.** This calls a series of macros which format the link data, node data, OD matrix, and intersection data spreadsheets based on the parameters specified. Pressing this button will erase anything which is currently in these sheets, so the interface will prompt for confirmation. Since these sheets are blank at this time, **click "Yes" when prompted.**

After creating these sheets, the interface will load the Link Data sheet. Enter the link parameters shown in Figure A.6. **Click on the "Proceed to node data" button**, which will advance you to the Node Data sheet. Enter the node parameters shown in Figure A.7, then **click on the "Proceed to OD Matrix" button**. You should see a blank matrix with entries for each of the possible origin-destination pairs in the network. The rows index the origin of travel, and the columns index the destination. As was stated at the start of the section, assume that 3000 vehicles depart from

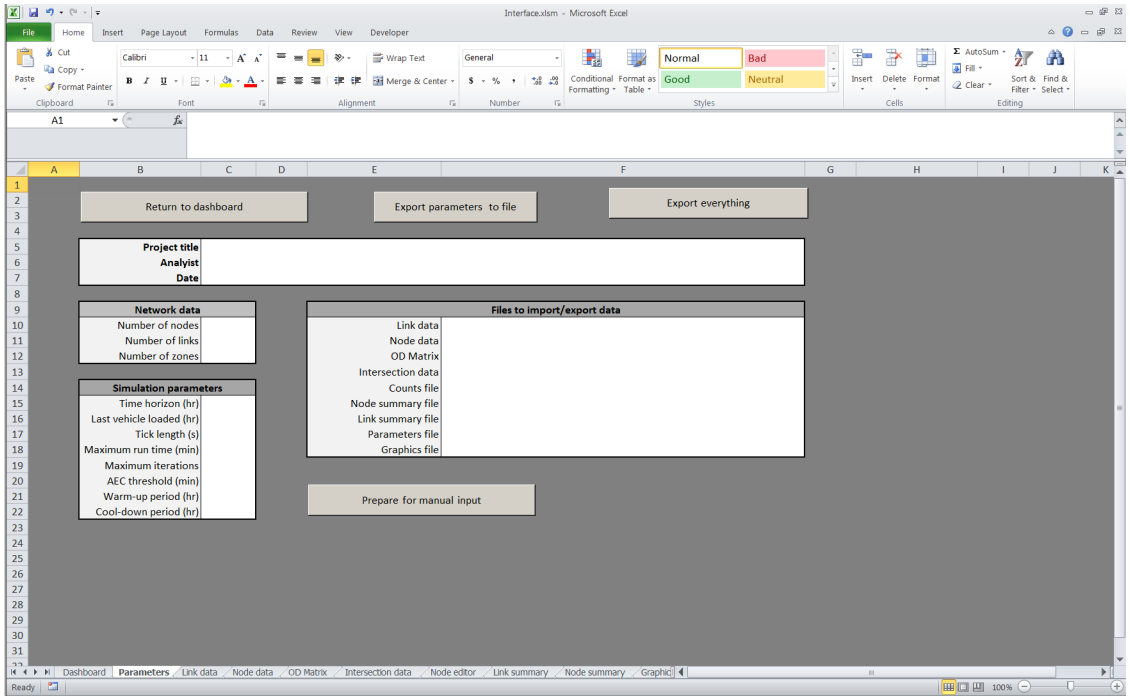


Figure A.4: Toy network parameters, blank.

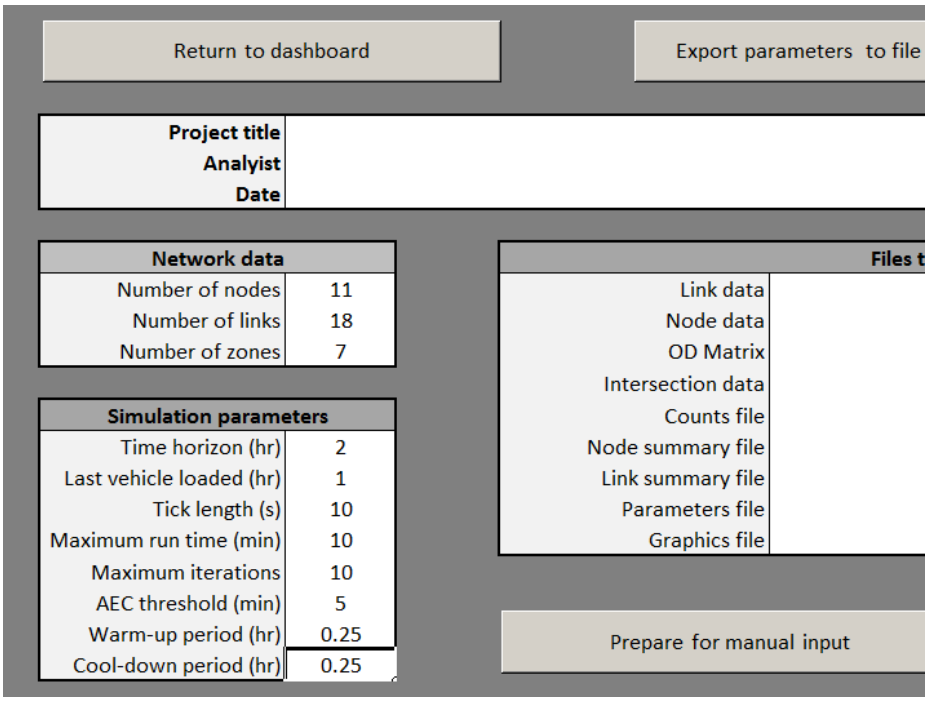
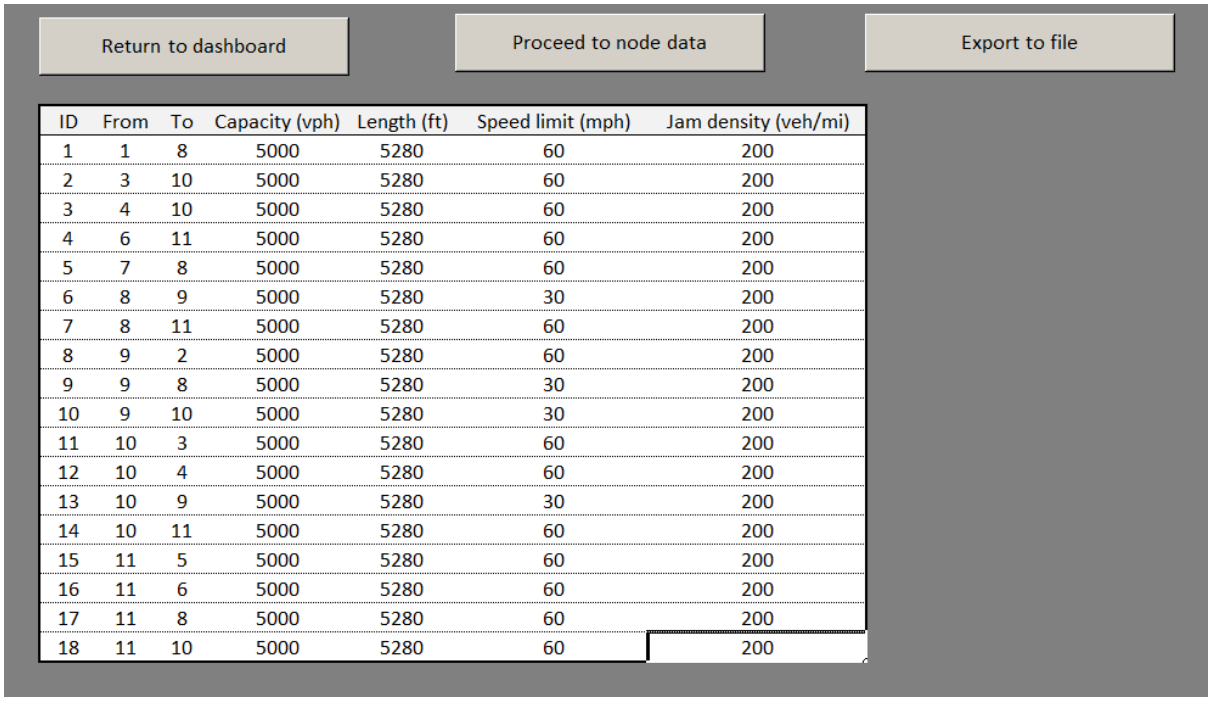


Figure A.5: Toy network parameters, completed.



ID	From	To	Capacity (vph)	Length (ft)	Speed limit (mph)	Jam density (veh/mi)
1	1	8	5000	5280	60	200
2	3	10	5000	5280	60	200
3	4	10	5000	5280	60	200
4	6	11	5000	5280	60	200
5	7	8	5000	5280	60	200
6	8	9	5000	5280	30	200
7	8	11	5000	5280	60	200
8	9	2	5000	5280	60	200
9	9	8	5000	5280	30	200
10	9	10	5000	5280	30	200
11	10	3	5000	5280	60	200
12	10	4	5000	5280	60	200
13	10	9	5000	5280	30	200
14	10	11	5000	5280	60	200
15	11	5	5000	5280	60	200
16	11	6	5000	5280	60	200
17	11	8	5000	5280	60	200
18	11	10	5000	5280	60	200

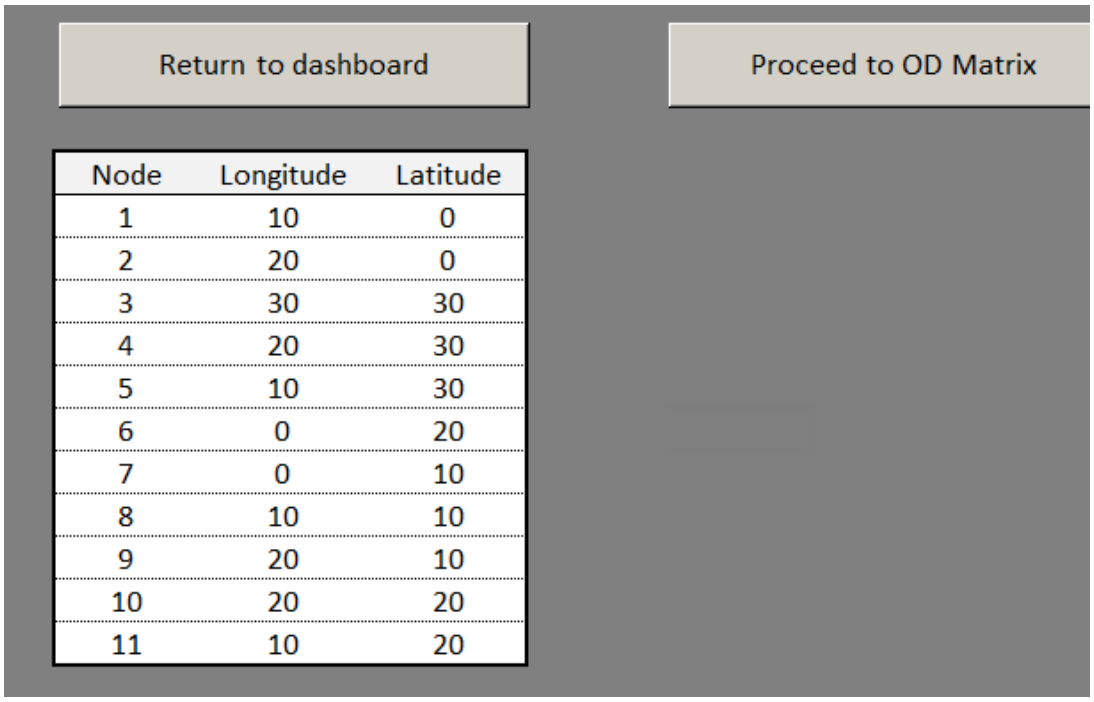
Figure A.6: Toy network link data, completed.

zone 1 to zone 3; 500 vehicles from zone to 3 to zone 6; 100 from zone 4 to zone 2; 500 from 6 to 3; and 200 from 7 to 2. **Enter these values into the sheet**, checking that your final result looks like Figure A.8, making sure that the rows and columns haven't been mixed up.

Click on "Proceed to intersection data," the final sheet for inputting data. The dropdown boxes in Column C indicate the different intersection control types for each intersection in the network. Nodes 1-7 are zones, and must have Centroid type. Since we don't know the control types for the other intersections, give them Unknown type. Before running a simulation, these will have to be filled in using the warrant analysis module. To do this, **click on "Return to dashboard."** Once on the dashboard, **click on "Warrant analysis (network)."**

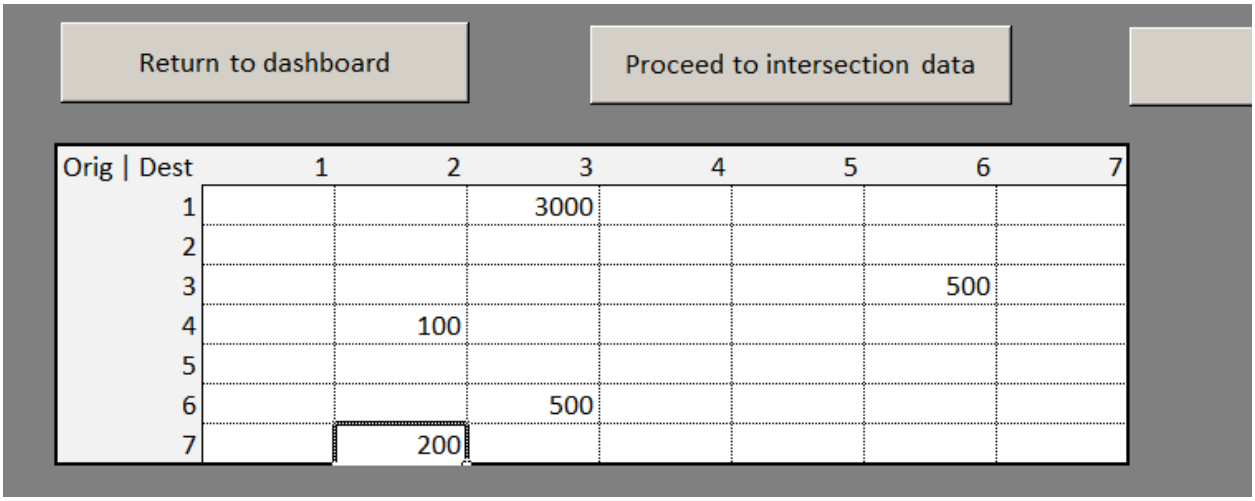
The first step in the warrant analysis is to export all of the information entered in the spreadsheet into the text files which the simulator will read. (You can also edit these text files directly, if desired.) Five dialog boxes will appear in sequence, asking you to enter the locations to save (a) the link data file, (b) the node data file, (c) the OD matrix, (d) the intersection control file, and (e) the parameters file. Enter the following information for each of these: (a) `toy_network.txt`, (b) `toy_nodes.txt`, (c) `toy_demand.txt`, (d) `toy_control.txt`, (e) `toy_parameters.txt`. The warrant analysis program will then run external to Excel, with control returning to the spreadsheet when it's finished.

At this point, if you explore the different spreadsheets in the file, you will notice a few changes. First, on the Parameters sheet, you will find the names of the filenames you typed (cf. Figure A.10, keeping in mind the exact path may differ depending on the folder you saved the files into). More importantly, on the Intersection Data sheet, you will see that nodes 8, 9, 10, and 11 no longer have



Node	Longitude	Latitude
1	10	0
2	20	0
3	30	30
4	20	30
5	10	30
6	0	20
7	0	10
8	10	10
9	20	10
10	20	20
11	10	20

Figure A.7: Toy network node data, completed.



Orig | Dest	1	2	3	4	5	6	7
1			3000				
2							
3						500	
4		100					
5							
6			500				
7		200					

Figure A.8: Toy OD matrix data, completed.

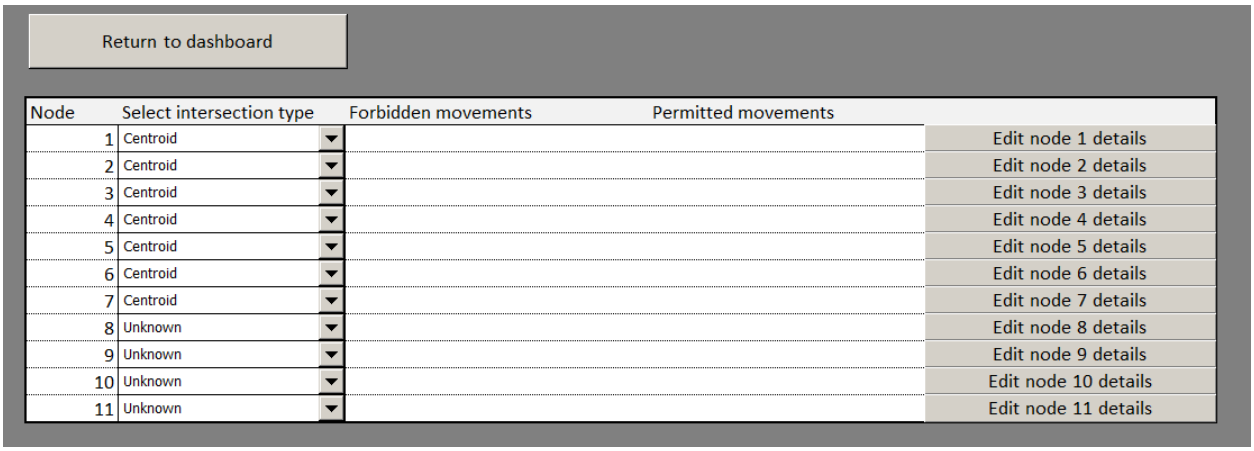


Figure A.9: Toy intersection data, completed.

Unknown type. Nodes 8 and 10 are now controlled by two-way stop, Node 9 by a four-way stop, and Node 11 by a signal, based on the warrant analysis which has been conducted. (Figure A.11).

To see more details on the signal timing chosen for node 11, **click on the "Edit node 11 details"** button. You should see the Node Editor sheet for node 11. Turning movement saturation flows are based on those of the upstream link, the cycle length was determined by Webster's Method, and the green times apportioned proportional to the degree of saturation for each approach. Now, let's edit this slightly: the green time for the approaches from link (10,11) seem very small. **Change the cycle length to 30, and the effective green times for movements `10 -> 11 -> 5`, `10 -> 11 -> 6`, and `10 -> 11 -> 8` to 13**, as shown in Figure A.13.

Now, we can run a full simulation to generate more detailed information. First, **click on "Save information and return to intersection data."** This step is very important; if you do not click this, your changes will not be saved. **Click on "Return to dashboard," and "Perform all steps without stopping."** This performs the following steps, in order:

1. Export the same 4 data files requested during the warrant analysis. (These files must be re-exported, because the warrant analysis changed the file configuration.) **use the same names as during the warrant analysis**.
2. Prompts you for the names of the three output files, the counts file, the node summary file, and the link summary file. **When prompted, enter `toy_counts.txt`, `toy_nodesummary.txt`, and `toy_linksummary.txt`.**
3. Export the parameters file; **use the same name as during the warrant analysis**.
4. Calls the mesoscopic simulation module, which run in a separate process.
5. Imports the link and node summary files.
6. Moves the user to the Link Summary spreadsheet.

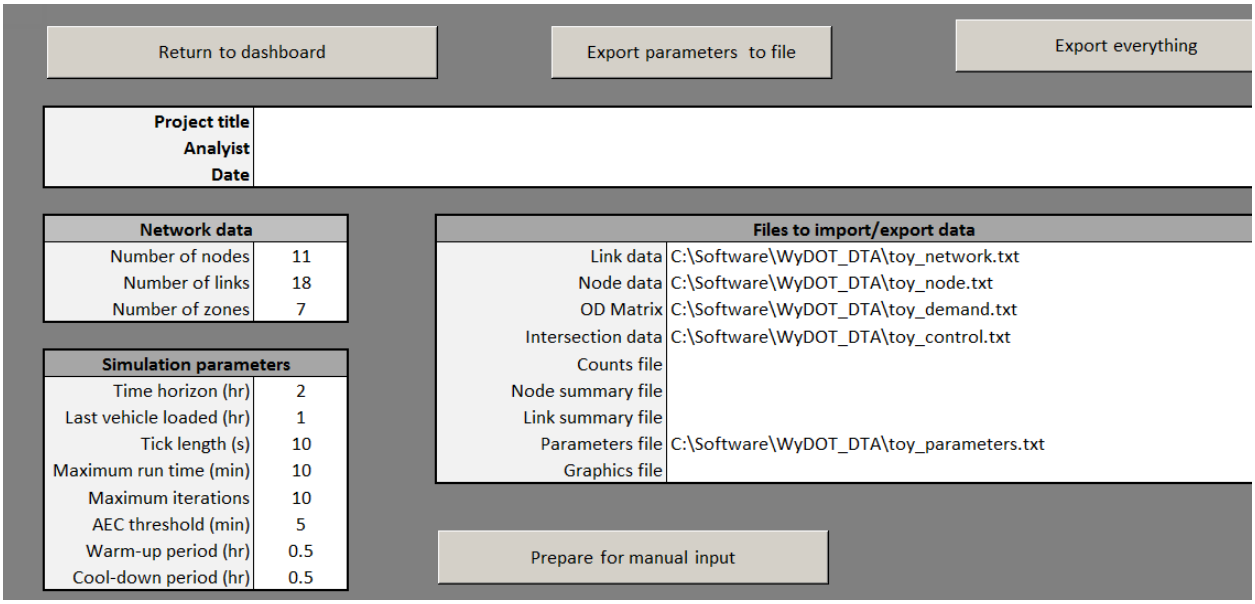


Figure A.10: File names have now appeared in the Parameters sheet.

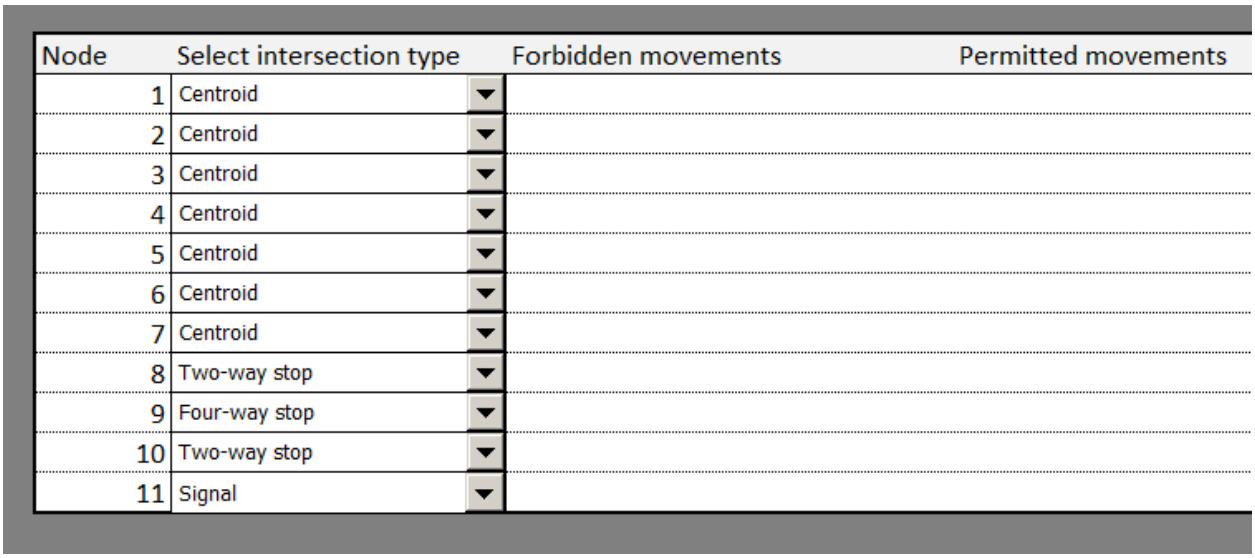
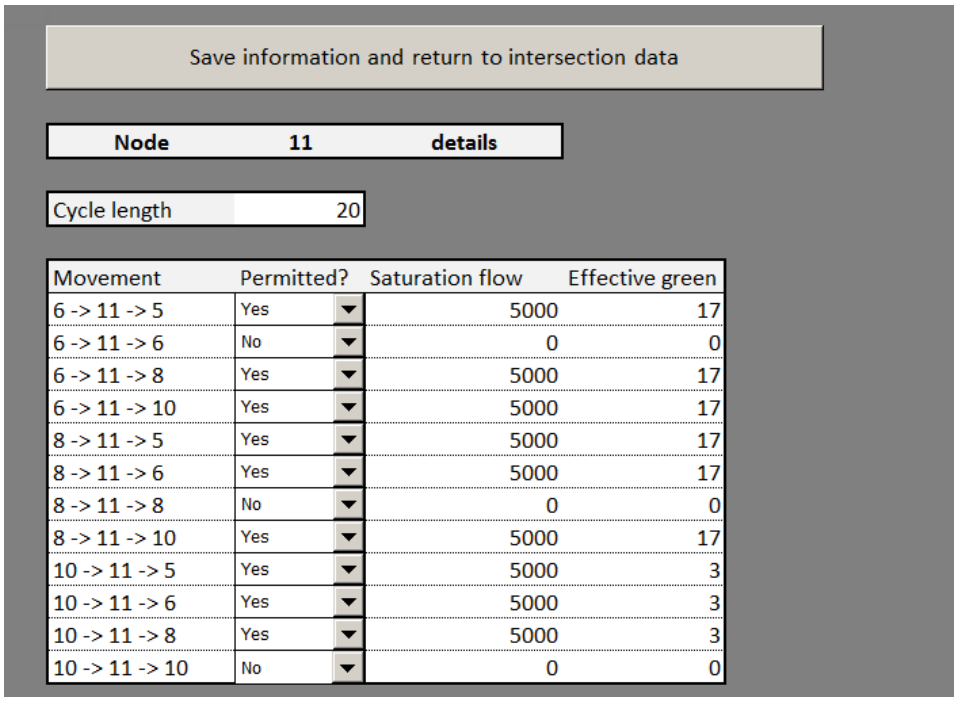
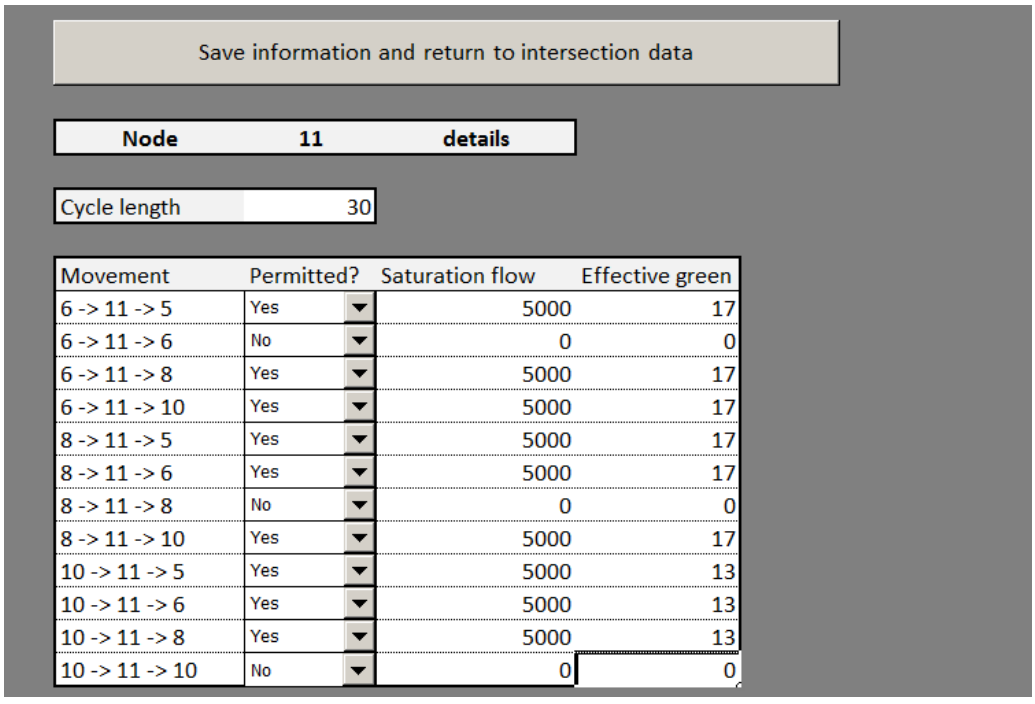


Figure A.11: Intersection types chosen by the warrant analysis.



Movement	Permitted?	Saturation flow	Effective green
6 -> 11 -> 5	Yes	5000	17
6 -> 11 -> 6	No	0	0
6 -> 11 -> 8	Yes	5000	17
6 -> 11 -> 10	Yes	5000	17
8 -> 11 -> 5	Yes	5000	17
8 -> 11 -> 6	Yes	5000	17
8 -> 11 -> 8	No	0	0
8 -> 11 -> 10	Yes	5000	17
10 -> 11 -> 5	Yes	5000	3
10 -> 11 -> 6	Yes	5000	3
10 -> 11 -> 8	Yes	5000	3
10 -> 11 -> 10	No	0	0

Figure A.12: Node details for node 11 from warrant analysis.



Movement	Permitted?	Saturation flow	Effective green
6 -> 11 -> 5	Yes	5000	17
6 -> 11 -> 6	No	0	0
6 -> 11 -> 8	Yes	5000	17
6 -> 11 -> 10	Yes	5000	17
8 -> 11 -> 5	Yes	5000	17
8 -> 11 -> 6	Yes	5000	17
8 -> 11 -> 8	No	0	0
8 -> 11 -> 10	Yes	5000	17
10 -> 11 -> 5	Yes	5000	13
10 -> 11 -> 6	Yes	5000	13
10 -> 11 -> 8	Yes	5000	13
10 -> 11 -> 10	No	0	0

Figure A.13: Modified details for node 11.

ID	From	To	Travel time (s)	Delay (s)	Density (veh/mi)	Volume (vph)	PHF
1	1	8	60	0	25	1533	0.75
2	3	10	60	0	4	255	0.73
3	4	10	60	0	1	44	0.53
4	6	11	60	0	4	251	0.72
5	7	8	60	0	2	104	0.7
6	8	9	120	0	4	108	0.72
7	8	11	60	0	26	1571	0.77
8	9	2	60	0	3	161	0.72
9	9	8	120	0	0	0	---
10	9	10	120	0	0	0	---
11	10	3	60	0	32	1910	0.8
12	10	4	60	0	0	0	---
13	10	9	120	0	2	49	0.59
14	10	11	60	0	4	261	0.74
15	11	5	60	0	0	0	---
16	11	6	60	0	4	267	0.76
17	11	8	60	0	0	0	---
18	11	10	61	1	31	1862	0.78

Figure A.14: Link summary information for toy network.

The Link Summary spreadsheet should appear as in Figure A.14. Note that the average density, volumes, and peak hour factors have been reported for each link in the network. Similar information appears in the Node Summary spreadsheet for each turning movement, sorted by the associated intersection. Finally, let's generate a graphics file using the data already obtained. **Click on "Generate 'average' graphic," and enter `toy_final.png` when prompted for the image name.** You should see the image in Figure A.15. This concludes the tutorial for the toy network.

A.2 Casper

The Casper tutorial shows how the simulator can be used on the city scale to model diversion for a work zone closure. This network is considerably larger than the toy network in the previous section: it contains 304 centroids, 1014 intersections, and 2760 roadway links. However, the `casper.xlsm` spreadsheet has the network data pre-loaded. The network and data were constructed from the TransCAD model used for long-range planning. The entire network is shown in Figure A.16. To simulate a work zone closure, the link representing Yellowstone Highway between Beverly St and C St is closed (represented in the simulator by deleting its link from the network file) (Figure A.17). Because this street is bidirectional, two links must be deleted — link 893 (connecting intersections 442 and 820) and link 2202 (connecting 820 and 442).

To examine the traffic conditions before the work zone is present, export all data, run the simulation, and import the simulation results as was done for the toy network. Zooming in to

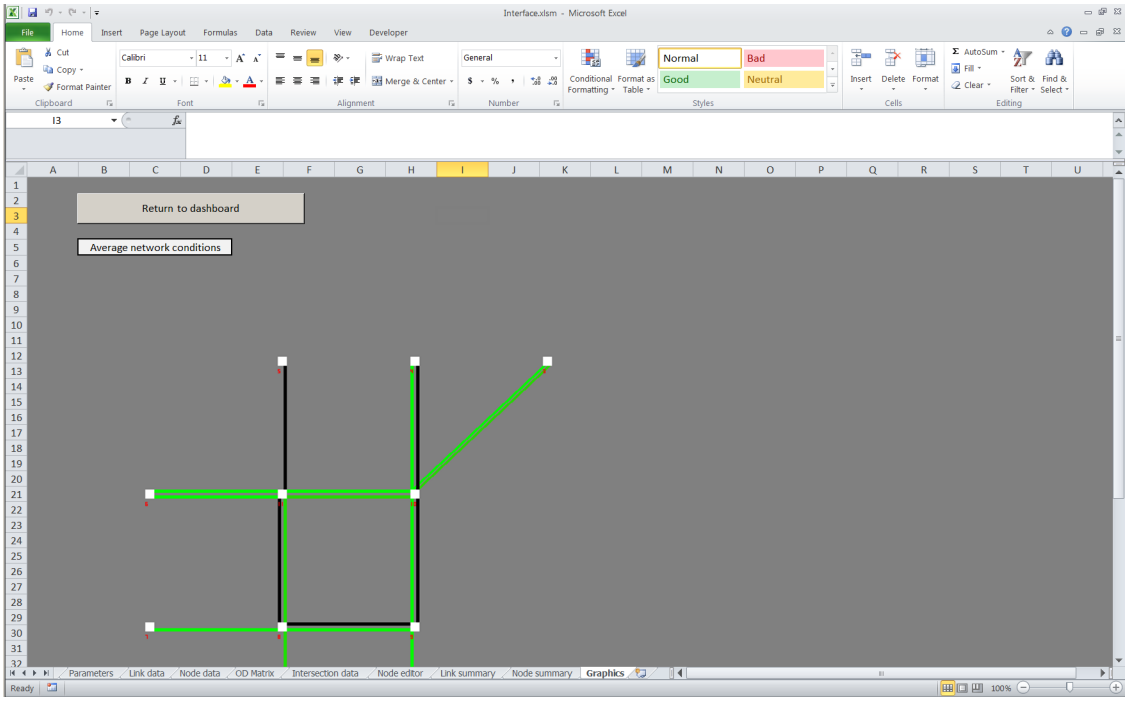


Figure A.15: Average graphics file for toy network.

node 436 (the intersection of Yellowstone Hwy & Beverly St), the flows for each turn movement can be recorded (and are shown in Table A.1).

To delete this link from the network, perform the following steps:

1. **On the Parameters sheet, decrease the number of links by 2.**
2. On the Link Data sheet, delete the rows for links 893 (connecting 442 and 820) and 2202 (connecting 820 and 442). To delete these, **select the entire row, and choose `Delete -> Delete Sheet Rows`** from the ribbon.
3. Export all data again, choosing different names to avoid overwriting the original results.
4. Run the simulation again.
5. Import the new results, and view the node summary file.

This obtains the updated flows shown in the right column of Table 4.1. Note the substantial diversion of flow away from this intersection after the closure. This reflects travelers choosing alternate routes to avoid the work zone and closure.

To find out how the traffic control should be revised to account for the change in flow, **click on "Warrant analysis (single node)"** on the dashboard. The single-node warrant analysis now looks at the revised flows, and makes the appropriate change on the Intersection Data worksheet. Clicking to this worksheet, one sees that the new recommended control at this intersection is a

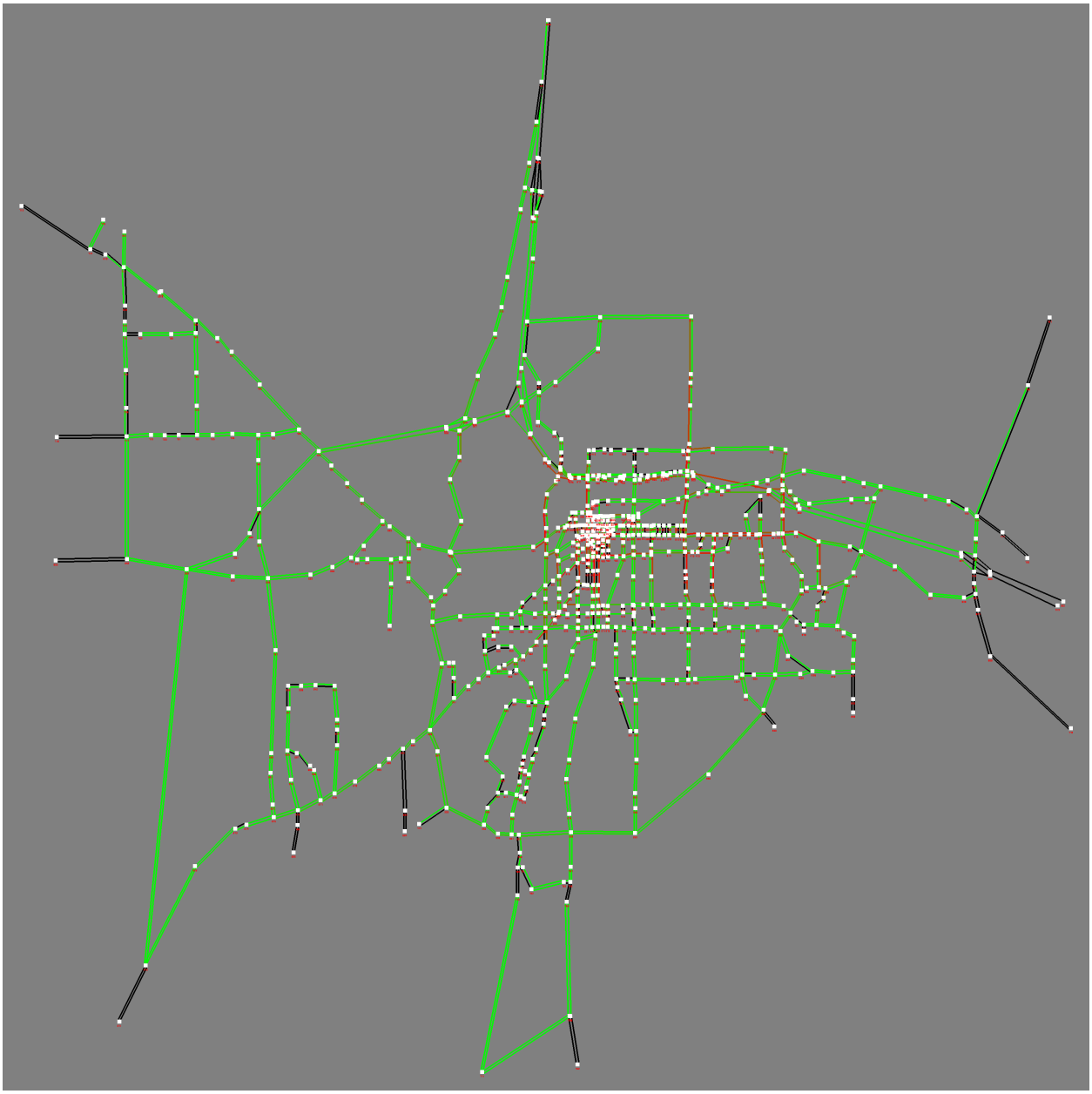


Figure A.16: Map of the entire Casper network.

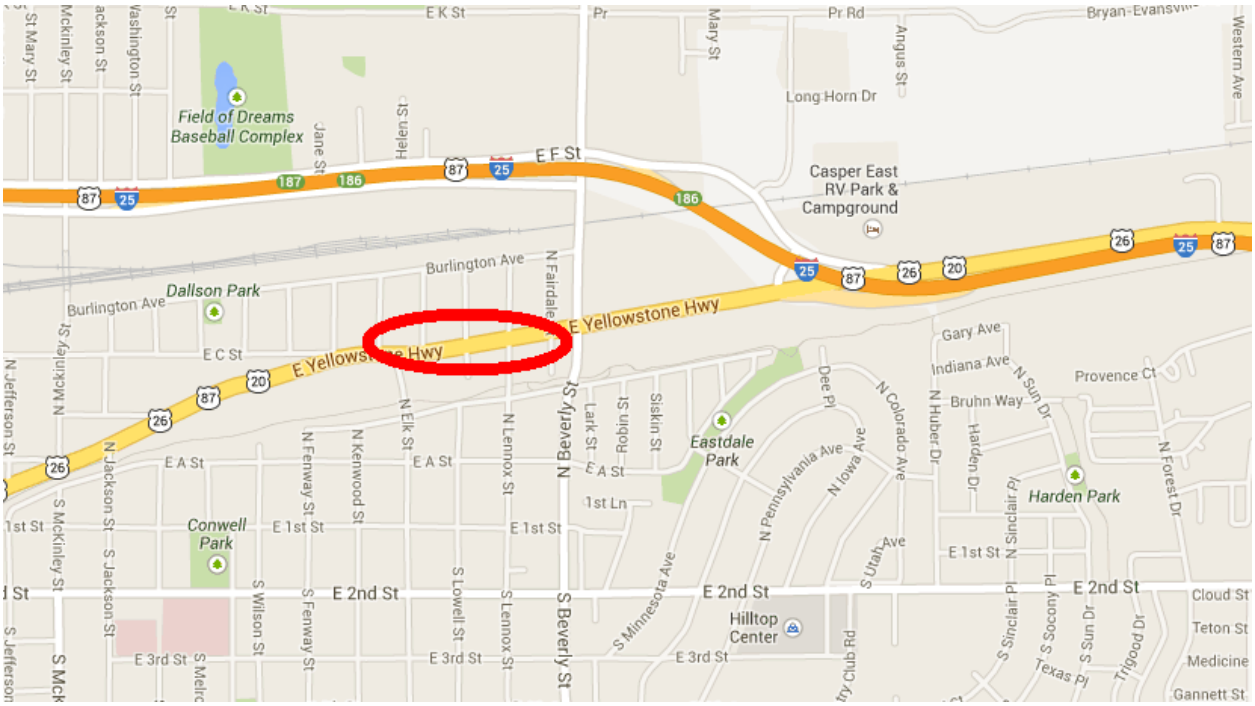


Figure A.17: Link closed for work zone.

Table A.1: Turning movement flows before and after closure of Yellowstone Hwy.

Movement	Flow before closure	Flow after closure
820 -> 436 -> 985	27	0
820 -> 436 -> 597	80	0
820 -> 436 -> 437	105	0
597 -> 436 -> 985	165	34
597 -> 436 -> 820	85	5
597 -> 436 -> 437	160	39
437 -> 436 -> 985	4	1
437 -> 436 -> 820	48	1
437 -> 436 -> 597	70	24
985 -> 436 -> 820	34	5
985 -> 436 -> 597	120	45
985 -> 436 -> 437	17	14

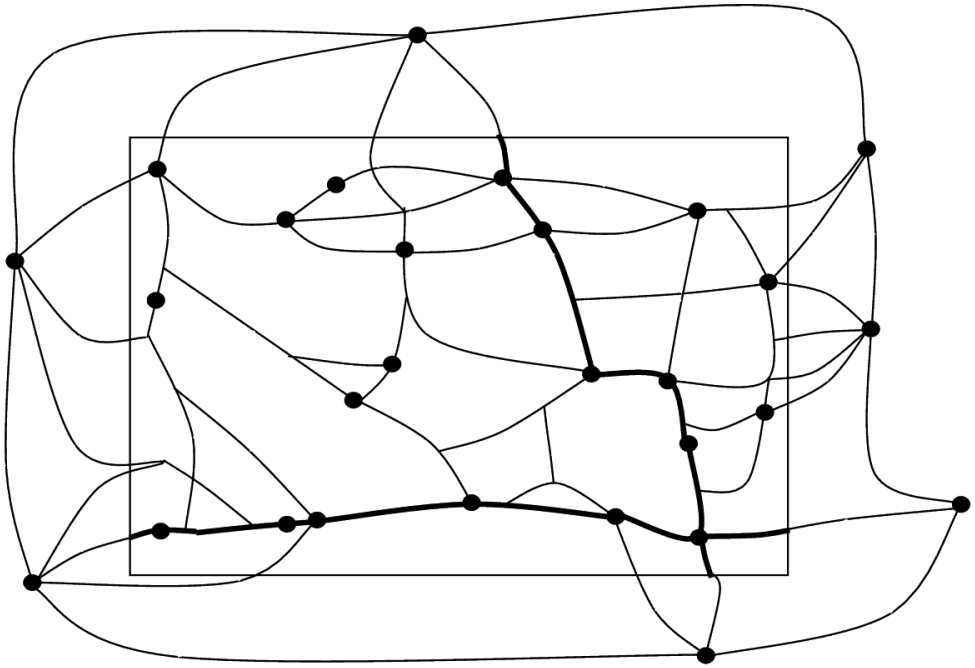


Figure A.18: Statewide network for Wyoming.

Four-Way Stop: due to diversion effects, this intersection sees much less traffic than before, and a four-way stop is sufficient to handle the traffic volumes. (This analysis only takes into account the traffic volume warrants. Particularly around work zones, safety factors may dictate another form of control.)

A.3 Wyoming

The last tutorial involves the Wyoming network. Like the Casper network, a "preloaded" version can be found in the spreadsheet `wyoming.xlsx`. The Wyoming network was constructed manually, including every interstate and federal highway in the State, along with several "external" intersections and links which represent diversion opportunities outside the state (Figure A.18). More details on the construction process can be found in Saha et al. (2013). The specific policy studied here was levying a toll on I-80 between Rock Springs and Rawlins, as suggested by Wyoming Department of Transportation (2008).

While the simulator does not directly model tolls on links, a toll can be effectively modeled by adjusting the free-flow speed of a link, as follows: to simulate a $20 toll, we increase the free-flow travel time on this link by an equivalent amount. This equivalency depends on travelers' value of time; this demonstration assumes an average $10/hr value of time, a standard figure in the tolling literature. This segment is 111 miles long, and has a speed limit of 75 mph. At this speed, the link takes 1.48 hours to traverse. At $10/hr value of time, the $20 toll imposes the equivalent of two additional hours of time, or an equivalent of 3.48 hours. This, in turn, translates to a speed of 32 mph for the 111 mile distance. Therefore, in the network file, the speed limit for I-80 was reduced

to 32 mph between Rock Springs and Rawlins to produce the same effect as a $20 toll. **This change is made on the Link Data sheet, to link 7 (connecting intersections 38 and 45) and link 117 (connecting intersections 45 and 38)**.

Viewing the link summary file, we can quantify the amount of diversion: prior to imposing the toll, the average annual daily traffic (AADT) count was approximately 6650 at this location, while after the toll, the AADT count decreased to 2800. Thus, approximately 3800 vehicles diverted onto an alternate route, primarily out-of-state traffic. This new AADT count can also be used to forecast toll revenue.

Appendix B

Source Code Guide

This appendix describes how the source code for the simulator is organized. As the complete source code has been provided to WYDOT, in the future WYDOT may wish to extend or modify the simulator in a variety of ways, and this appendix helps orient programmers to the structure of the code. Efforts have been made to make the code modular and easy to understand, using principles of structured programming. This appendix does not provide details on the methodology or general flow of the algorithm, which are provided in Chapters 2 and 3, respectively.

The simulator was written in C, and is compatible with the ANSI C89 standard. (Virtually any modern C compiler should be able to compile to this standard.) The simulator code is spread across ten source files and ten header files. These files are generally organized in a hierarchical manner, as shown in Figure B.1, in the sense that source files call on functions or use data structures of equal or lower hierarchy, but not functions or data structures from higher files in the hierarchy. There are a few exceptions to this rule, where strict obedience would lead to convoluted or confusing solutions, but in the large majority of instances the code respects this organization. This facilitates compilation order and makefile creation.

Each file is briefly described as follows, starting from the bottom of the hierarchy and working up:

1. `utils.c` and `utils.h`: These files define basic macros and functions used throughout the code. These include basic mathematical functions not included in the standard libraries (e.g., maximization, minimization, and rounding), definition of a boolean data type (if not being compiled in C++ mode), defining the verbosity levels for status messages, and providing logging functions to display messages and warnings (based on the verbosity level), and fatal errors (regardless of the verbosity level).

2. `sampling.c` and `sampling.h`: These files contain the code used to generate random numbers from different distributions. The most important for the simulator are `roundStochastic`, which employs stochastic rounding to convert floating-point numbers to integers (e.g., since vehicles are modeled in a discrete fashion, fractional flows cannot be created) and the function `roundStochasticMatrix`, which stochastically rounds a

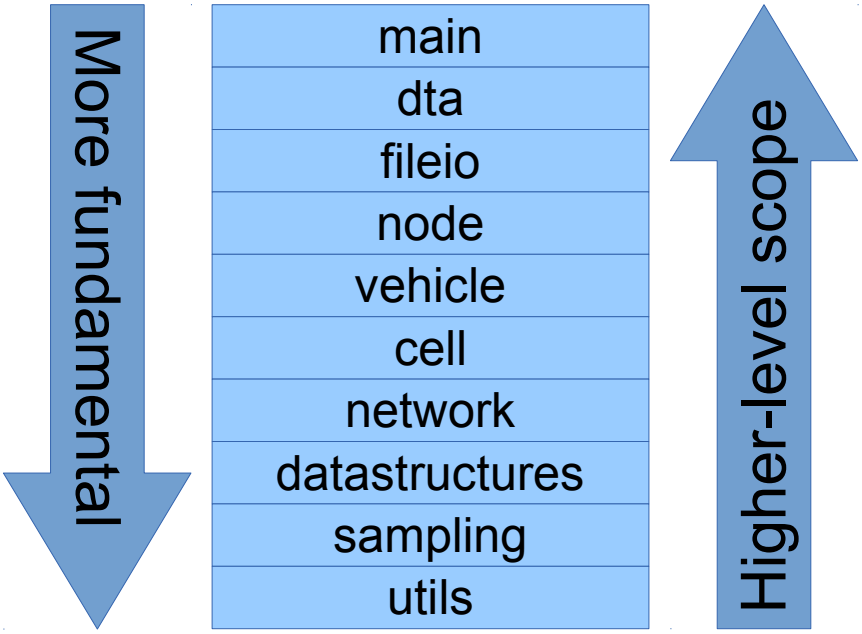


Figure B.1: Hierarchy of source files.

floating-point matrix to integers while preserving row and column sums to the extent possible.

3. `datastructures.c` and `datastructures.h`: These files define basic data structure templates for singly and doubly linked lists, queues, and binary heaps. These are general-purpose data structures, and more specific implementations are described in files higher in the hierarchy. Additionally, custom memory allocation and deallocation routines are provided, with optional memory-leak checking. These routines are discussed in more detail below.

4. `network.c` and `network.h`: These files establish the data structures for general network modeling, along with standard network algorithms. **This file contains the core module `TDAStar`, which implements the time-dependent A* algorithm.** The data structures in this file are extremely important, and are discussed in more detail below.

5. `cell.c` and `cell.h`: These files contain the data structures and routines related to the vehicles themselves, and their propagation from one cell to another, from roadway links to turning movements, and vice versa. Gap calculations for the convergence criteria are also found in these files.

6. `vehicle.c` and `vehicle.h`: These files contain the data structures and routines related to the vehicles themselves, and their propagation from one cell to another, from roadway links to turning movements, and vice versa. Gap calculations for the convergence criteria are also found in these files.

7. `node.c` and `node.h`: These files contain the routines for the node processing algorithm described in Sections 2.2.5 and 3.2.1. If users wish to modify the algorithms used for intersection processing (or to introduce a new intersection control type), these files will be the primary place these modifications are made.

8. `fileio.c` and `fileio.h`: These files contain the routines for reading input data files, and writing output data files. Additional string processing routines are included here to parse metadata tags and values, identify comments in the input line, and so forth.

9. `dta.c` and `dta.h`: These files contain the general control loop for dynamic traffic assignment. In particular, **these files contain the core modules `simulateCTM` and `shiftMSA`, which implement the cell transmission model and method of successive averages.** Additional functions provide for allocation and deallocation of the traffic assignment run structures.

10. `main.c` and `main.h`: These brief files handle control when the program is first run, checking that the necessary number of parameters has been provided, and then transferring control to the DTA processing code.

The following features of the source code warrant further documentation: the units system; the memory allocation and deallocation system; the implementation of linked lists; and network algorithms which function in the dual graph.

The code uses a consistent internal system of units, measuring all times in seconds and all distances in feet. However, it is often more convenient to provide input or output in different units. The follow macros provided in `utils.h` facilitate units conversion:

```
#define HOURS      3600.0
#define MINUTES    60.0
#define SECONDS    1.0
#define MILES      5280.0
#define KILOMETERS 3280.839895
#define METERS     3.280839895
#define FEET       1.0
#define INCHES     0.083333333
```

Multiplying by one of these macros converts a quantity into standard units, while dividing converts it out of standard units. For instance, if `t = 3` and `t` is measured in hours, then `t * HOURS` will give the proper number of seconds. If `u` is measured in seconds (the standard unit), but we want to report the answer in hours, then `t / HOURS` will give the correct number of hours. Caution should be used when units appear in the denominator. As an example, if `v` is measured in miles per hour, then converting to standard units would require `v * MILES / HOURS`, while converting `v` from internal units to miles per hour would require `v / (MILES / HOURS)` or `v * HOURS / MILES`. If a programmer wishes to change the internal system of units, all that needs to be changed are the relative values in this file, and the code will seamlessly change. (The internal units are those corresponding to `1.0` values in this list.)

Memory allocation and deallocation is facilitated by the following macros, which are defined in `datastructures.h`:

```
#define newScalar(y) (y *)allocateScalar(sizeof(y))
#define newVector(u,y) (y *)allocateVector(u,sizeof(y))
#define newMatrix(u1,u2,y) (y **)allocateMatrix(u1,u2,sizeof(y))
#define new3DArray(u1,u2,u3,y) (y ***)allocate3DArray(u1,u2,u3,sizeof(y))

#define declareScalar(y,S) y *S = newScalar(y)
#define declareVector(y,V,u) y *V = newVector(u,y)
#define declareMatrix(y,M,u1,u2) y **M = newMatrix(u1,u2,y)
#define declare3DArray(y,A,u1,u2,u3) y ***A = new3DArray(u1,u2,u3,y)

#define deleteScalar(y) killScalar(y)
#define deleteVector(y) killVector(y)
#define deleteMatrix(y,u1) killMatrix((void **)y,u1)
#define delete3DArray(y,u1,u2) kill3DArray((void ***)y,u1,u2)
```

These routines allow users to allocate and deallocate memory for scalars (single variables), vectors (one-dimensional arrays), matrices (two-dimensional arrays), and three-dimensional arrays. To use the `newScalar`, `newVector`, `newMatrix`, and `new3DArray` macros, the relevant dimensions are specified, followed by the data type. These are used as right-hand expressions; the left-hand side should be a pointer of the appropriate type. For instance, to allocate a vector of 5 `double`s, the code

```
double x* = newVector(5, double)
```

can be used. For convenience, a more compact shorthand is available when simultaneously declaring and allocating an array, the macros `declareScalar`, `declareVector`, `declareMatrix`, and `declare3DArray` which are used as follows:

```
declareVector(double, x, 5)
```

which is identical to the previous code snippet.

To deallocate memory, the relevant `deleteX` macro can be called. For multidimensional arrays, you must specify all dimensions except the last. All of these macros reference routines in `datastructures.c` which include error checking and input validation.

The network data structure is extremely important, and forms the backbone of the cell transmission model. As shown schematically in Figure B.2, the `network_type` data structure contains the following elements:

- `arc`, an array storing every roadway link, of type `arc_type` (see description below).

- `node`, an array storing every intersection, of type `node_type` (see description below).
- `ODT`, an array storing every origin-destination-time combination, of type `ODT_type` (see description below).
- `paths`, a linked list storing every route which has been generated during the simulation run.
- `origin`, an artificial arc where vehicles are placed before they depart on trips.
- `destination`, an artificial arc where vehicles are placed after they complete their trips.
- `sink`, an artificial node corresponding to the `origin` and `destination` arcs.
- `staticOD`, a two-dimensional array storing the demand matrix read from the file.
- A number of parameters specific to the network, such as the total number of vehicles assigned, simulation tick length, sizes of the above arrays, and so forth.

Arcs, nodes, and ODTs form their own structures. An arc contains the following elements:

- `cells`, a linked list representing each of the cells the link has been divided into.
- `turnMovements`, a linked list containing pointers to each turning movement at the downstream end of the link.
- `upstreamMovements`, a linked list containing pointers to each turning movement at the upstream end of the link.
- `tail`, a pointer to the node at the upstream end of the intersection.
- `head`, a pointer to the node at the downstream end of the intersection.
- `travelTime`, an array giving the integer travel time for a vehicle entering at each time interval.
- `upstreamCount`, an array giving the cumulative count at the upstream end of the arc at each time interval.
- `downstreamCount`, an array giving the cumulative count at the downstream end of the arc at each time interval.
- `freeFlowToDest`, an array giving the free-flow travel time to each destination (used in time-dependent A*).
- `freeFlowMovement`, an array storing the fastest routes at free-flow (used if the time horizon will be exceeded).
- A number of parameters specific to the link, such as the jam density, free-flow travel time, and so forth.

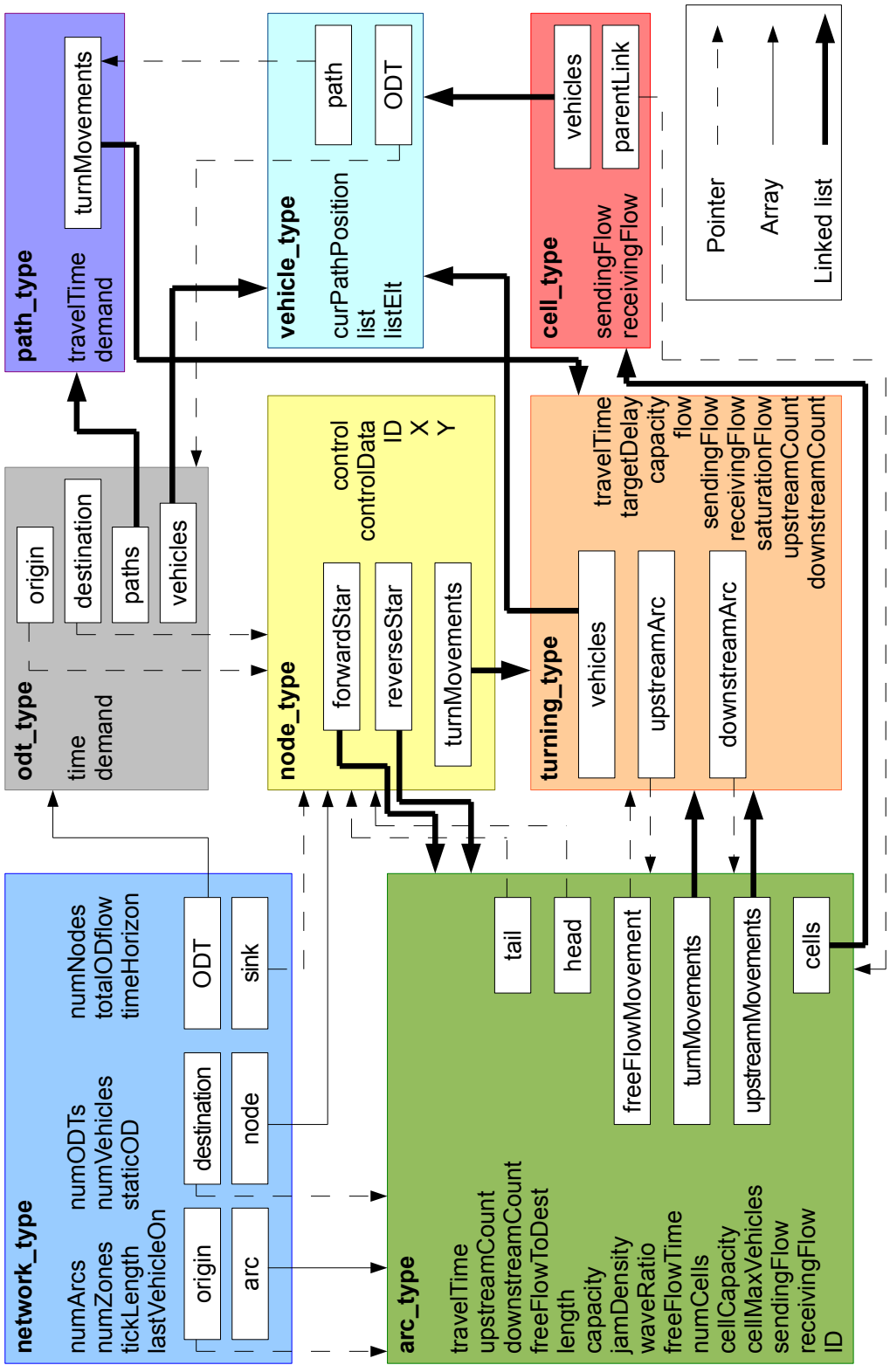


Figure B.2: Schematic of network-related data structures.

A node contains the following elements:

- `forwardStar`, a linked list of the arcs emanating from this node.
- `reverseStar`, a linked list of the arcs terminating at this node.
- `turnMovements`, a linked list of all turning movements corresponding to this intersection.
- `intersectionControl`, an `enum` specifying the traffic control method at the intersection.
- `controlData`, a data structure which may be created for particular traffic control types, and which takes different forms based on the control type (see `node.h` for details).

An ODT contains the following elements:

- `origin`, a pointer to the origin centroid.
- `destination`, a pointer to the destination centroid.
- `departureTime`, the departure time corresponding to this ODT.
- `demand`, the number of vehicles corresponding to this ODT.
- `vehicles`, a doubly linked list containing pointers to each vehicle associated with this ODT.
- `paths`, a linked list of routes which are used by vehicles from this ODT.

A turning movement contains the following elements:

- `vehicles`, a doubly linked list containing pointers to each vehicle in the turning movement cell.
- `upstreamArc`, a pointer to the arc that the turning movement is coming from.
- `downstreamArc`, a pointer to the arc that the turning movement is heading to.
- `travelTime`, an array listing the travel time for vehicles entering the turning movement at any time.
- `upstreamCount`, an array listing the upstream cumulative count $N^{\uparrow}$ at any time.
- `downstreamCount`, an array listing the upstream cumulative count $N^{\downarrow}$ at any time.
- A number of parameters specific to the movement, such as its capacity and target delay.

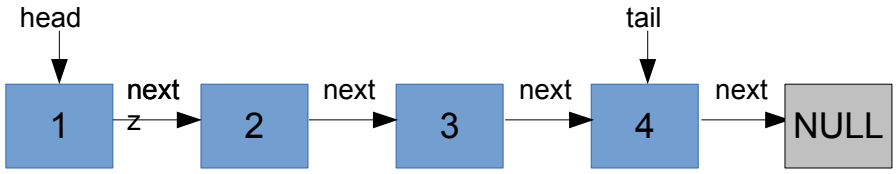


Figure B.3: Schematic of linked list data structures.

Paths, vehicles, and cells are important secondary data structures. A path primarily consists of a linked list of turning movements — it isn't necessary to store the specific links in the path, because a sequence of turning movements implies the roadway links themselves. The vehicle data structure includes the following elements:

- `path`, a pointer to the path the driver of the vehicle is using.
- `curPathPosition`, a pointer into the path's list of turn movements, to show the current position of the vehicle.
- `list`, a pointer to the linked list the vehicle is stored in. Every vehicle is always stored in a vehicleDoublyLinkedList, either on the artificial origin arc, artificial destination arc, or a link or turning movement vehicle list. Storing this pointer greatly speeds up the process of moving vehicles.
- `listElt`, a pointer to the specific position within the linked list the vehicle is stored in. Storing this pointer greatly speeds up the process of moving vehicles.

A cell includes the following elements:

- `vehicles`, a doubly linked list pointing to the vehicles currently in the cell.
- `parentLink`, a pointer to the roadway link the cell belongs to (this avoids having to duplicate all link parameters in each cell).
- `sendingFlow` and `receivingFlow`, used in the flow propagation model (cf. Section 2.2.4).

Many types of linked lists are used in the code, to store variable-length arrays (such as lists of paths, vehicles, cells, and so forth). While slightly different information is stored in each type of linked list, they all have a common form (Figure B.3). The arc linked list provides a good example for demonstration:

```
typedef struct arcLinkedListElt_s {
arc_type *arc;
struct arcLinkedListElt_s *next;
} arcLinkedListElt;

typedef struct arcLinkedList_s {
arcLinkedListElt *head;
arcLinkedListElt *tail;
int size;
} arcLinkedList;
```

where the head and tail are initialized to the `NULL` pointer. Notice that the linked list does not store the arc itself, but a pointer to it. This saves memory and increases computation time. Very frequently, the code must iterate over every element in a linked list. This is commonly done using a `for` loop using the following syntax:

```
for (curArc = network->node[i].forwardStar->head;
curArc != NULL;
curArc = curArc->next) {
...
}
```

Here, `network->node[i].forwardStar` is an `arcLinkedList` storing all the arcs emanating from intersection `i`. `curArc` iterates in turn over every element in the linked list. Notice that `curArc` is *not* the arc element itself, but rather the list element. To access the corresponding arc, you need to use `curArc->arc`.

Appendix C

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Appendix D

Simulator code

D.1 Mesoscopic simulation module

D.1.1 `main.c`

```
1  #include "main.h"
2
3  /*
4  main -- Primary file for running mesoscopic simulation
5  */
6  int main(int numArgs, char *args[]) {
7
8    parameters_type run;
9     verbosity = FULL_NOTIFICATIONS;
10
11    #ifdef DEBUG_MODE /* Debug mode enables extra logging.  Define this
          macro in utils.h */
12       debugFile = openFile("logfile.txt", "w");
13    #endif
14
15    if (numArgs != 2) displayUsage();
16
17   initializeDTARun(&run, args[1]);
18    DTA(&run);
19
20    if (strlen(run.countsFileName)) writeCumulativeCounts(run.network,
          run.countsFileName);
21    if (strlen(run.linkSummaryName)) writeLinkSummary(&run, run.
          linkSummaryName);
22    if (strlen(run.nodeSummaryName)) writeNodeSummary(&run, run.
          nodeSummaryName);
```

```
23
24    cleanUpDTARun(&run);
25
26     #ifdef DEBUG_MODE
27        fclose(debugFile);
28     #endif
29
30    return (EXIT_SUCCESS);
31  }
32
33  /*
34  displayUsage -- provides instructions to the user if the incorrect
       number of command-line arguments is given.
35  */
36  void displayUsage() {
37    fatalError("Must provide exactly one argument (parameters file).");
38  }
```

D.1.2 main.h

```
1   /*
2    Hierarchy of header files (bottom-up):
3
4    utils.h
5    datastructures.h
6    sampling.h
7    network.h
8    cell.h
9    vehicle.h
10   node.h
11   fileio.h
12   dta.h
13   Optional modules can be included here: warrant.h, graphics.h
14   main.h
15
16   Declarations referring to lower-level headers can use typedefs;
        declarations referring to higher-level headers must use structs
17  */
18
19
20  #include <stdlib.h>
21  #include "cell.h"
22  #include "fileio.h"
23  #include "utils.h"
24  #ifdef GRAPHICS_MODE
25     #include "graphics.h"
26  #endif
```

```
27 #include "warrant.h"
28
29 void displayUsage();
```

D.1.3 dta.c

```
1  #include "dta.h"
2
3  /*
4  DTA -- controls the main DTA loop.
5  Arguments:
6     run -- pointer to a parameters_type containing all the DTA run
          parameters
7  */
8  void DTA(parameters_type *run) {
9    network_type *network = run->network;
10   bool isConverged = FALSE;
11   int iteration = 0;
12   clock_t startTime = clock();
13   double elapsedTime = 0;
14   float gap = INFINITY;
15
16   initializeTravelTimes(network); /* Initializes travel times to free-
        flow */
17   addShortestPaths(network);      /* Add initial SPs to path set for
        each ODT */
18    initializeVehicles(network);
19    updateElapsedTime(startTime, &elapsedTime);
20    displayMessage(MEDIUM_NOTIFICATIONS, "Ready to start main loop.\n");
21
22
23   while (isConverged == FALSE) {
24     iteration++;
25     startTime = clock();
26
27     simulateCTM(network);
28     updateAllTravelTimes(network);
29     addShortestPaths(network);
30
31     updateElapsedTime(startTime, &elapsedTime);
32     gap = averageExcessCost(network);
33     displayMessage(MEDIUM_NOTIFICATIONS, "Iteration %d: AEC %f in %f
          seconds (latest arrival %d)\n", iteration, gap, elapsedTime,
          latestArrivalTime(network));
34     if (gap < run->AECtarget || iteration >= run->maxIterations ||
          elapsedTime > run->maxRunTime) break;
35
```

```
36      shiftMSA(network, 1.0 / (iteration + 1));
37    }
38  }
39
40  /*
41  simulateCTM -- performs cell transmission model loading when all
        vehicles have already been assigned paths.
42  Arguments:
43     network -- pointer to a network_type containing the network and all
           relevant parameters
44
45  Simulation works as follows:
46    In *increasing order of time*
47      1. Load vehicles onto origin movements based on *paths*
48      2. Identify each cell's sending and receiving flow
49      3. Process links:
50           Transfer vehicles for *interior cells.*  Find the # of vehicles
                , move that many from the end of upstream queue to back of
                downstream queue
51      4. Process nodes:
52           Go to a splitting function based on the node type.  Works based
                on sending/receiving flows, also updates cumulative counts
53  */
54  #define CTM_REPORTING_INTERVAL 100
55  void simulateCTM(network_type *network) {
56    int i, ij, t;
57    int odt = 0;
58    vehicleDoublyLinkedListElt *curVehicle;
59
60    prepareAllTrips(network); /* Load all vehicles on origin link */
61    initializeCounts(network);
62    initializeNodes(network);
63    for (t = 0; t < network->timeHorizon; t++) {
64
65      /* Initialize new cumulative counts to old ones */
66      if (t > 0) copyCounts(network, t-1, t);
67
68      /* Load flows at origin nodes.  This implementation exploits the
           temporal ordering of the ODT array */
69      if (odt < network->numODTs) {
70        while (network->ODT[odt].departureTime == t) {
71          for (curVehicle = network->ODT[odt].vehicles->head; curVehicle
                != NULL; curVehicle = curVehicle->next) {
72            transferVehicleToMovement(curVehicle->vehicle, &(network->
                  origin), curVehicle->vehicle->curPathPosition->movement, t
                  );
73          }
```

```
74          if (++odt >= network->numODTs) break;
75        }
76      }
77
78      /* Calculate sending and receiving flows for all cells, and shift
            flows within an arc */
79      for (ij = 0; ij < network->numArcs; ij++) {
80        calculateSendingFlows(&network->arc[ij]);
81        calculateReceivingFlows(&network->arc[ij]);
82        moveIntralinkVehicles(&network->arc[ij]);
83      }
84
85      /* Now process each node, according to its control type */
86      for (i = 0; i < network->numNodes; i++) {
87        processNode(network, &(network->node[i]), t);
88      }
89
90      if (t % CTM_REPORTING_INTERVAL == 0) displayMessage(
            FULL_NOTIFICATIONS, "Simulated %d of %d ticks (%d%%)\r", t,
            network->timeHorizon, 100 * t / network->timeHorizon);
91    }
92    displayMessage(FULL_NOTIFICATIONS, "Simulated %d of %d ticks (%d%%)\n
         ", network->timeHorizon, network->timeHorizon, 100);
93
94    terminateAllTrips(network); /* Clean up any vehicles still left on
         the network by moving to destination and warn about incomplete
         trips */
95  }
96
97  /*
98  shiftMSA -- Changes path choices based on method of successive averages
       , using stochastic selection.
99  Arguments:
100     network -- pointer to a network_type containing the network and all
            relevant parameters
101     movingFraction -- probability to move vehicles onto the shortest
            path.  Generally 1/(iteration+1), but this function can be called
             with any fraction
102 */
103 void shiftMSA(network_type *network, float movingFraction) {
104   int odt;
105   double minPathCost;
106   vehicleDoublyLinkedListElt *curVehicle;
107   pathLinkedListElt *curPath;
108   path_type *targetPath;
109
110   for (odt = 0; odt < network->numODTs; odt++) {
```

```
111      /* Find min-cost path */
112      minPathCost = network->timeHorizon + 1;
113      for (curPath = network->ODT[odt].paths->head; curPath != NULL;
             curPath = curPath->next) {
114        if (curPath->path->travelTime < minPathCost) {
115          minPathCost = curPath->path->travelTime;
116          targetPath = curPath->path;
117        }
118      }
119      if (targetPath == NULL) fatalError("No paths exist for odt %d -> %d
             @ %d\n", network->ODT[odt].origin->ID, network->ODT[odt].
            destination->ID, network->ODT[odt].departureTime);
120      for (curVehicle = network->ODT[odt].vehicles->head; curVehicle !=
            NULL; curVehicle = curVehicle->next) {
121        if (randUniform(0, 1) < movingFraction) {
122          curVehicle->vehicle->path->demand--;
123          curVehicle->vehicle->path = targetPath;
124          curVehicle->vehicle->path->demand++;
125        }
126      }
127    }
128  }
129
130  /*
131  cleanUpDTARun -- Deallocates memory associated with a DTA run.
132  Splits into deleteSchedule and deleteNetwork so the latter can be
        called separately
133  when memory has only been partially allocated (as in warrant analysis
        runs)
134  Arguments:
135     run -- pointer to a parameters_type containing all the DTA run
           parameters
136  */
137  void cleanUpDTARun(parameters_type *run) {
138     deleteSchedule(run->network);
139     deleteNetwork(run->network);
140     if (run->demandProfile == TRIANGLE) deleteScalar(run->
           profileParameters);
141  }
142
143  /*
144  deleteSchedule -- Deallocates memory associated with the time-dependent
         data structures of a network
145  Arguments:
146     network -- pointer to a network_type containing all relevant
           parameters
147  */
```

```
148 void deleteSchedule(network_type *network) {
149   int i, ij, odt;
150   cellDoublyLinkedListElt *curCell;
151   turningLinkedListElt *curMovement;
152   vehicleDoublyLinkedListElt *curVehicle;
153
154   for (ij = 0; ij < network->numArcs; ij++) {
155     deleteVector(network->arc[ij].travelTime);
156     deleteVector(network->arc[ij].upstreamCount);
157     deleteVector(network->arc[ij].downstreamCount);
158     for (curCell = network->arc[ij].cells->tail; curCell != NULL;
          curCell = curCell->next) {
159       deleteVehicleDoublyLinkedList(curCell->cell->vehicles);
160       deleteScalar(curCell->cell);
161     }
162     deleteCellDoublyLinkedList(network->arc[ij].cells);
163     deleteVector(network->arc[ij].freeFlowToDest);
164     deleteVector(network->arc[ij].freeFlowMovement);
165   }
166   deleteVector(network->origin.travelTime);
167   deleteVector(network->origin.upstreamCount);
168   deleteVector(network->origin.downstreamCount);
169   deleteVector(network->destination.travelTime);
170   deleteVector(network->destination.upstreamCount);
171   deleteVector(network->destination.downstreamCount);
172
173    for (i = 0; i < network->numNodes; i++) {
174     for (curMovement = network->node[i].turnMovements->head;
          curMovement != NULL; curMovement = curMovement->next) {
175       deleteVector(curMovement->movement->travelTime);
176       deleteVector(curMovement->movement->upstreamCount);
177       deleteVector(curMovement->movement->downstreamCount);
178     }
179    }
180
181   for (odt = 0; odt < network->numODTs; odt++) {
182     for (curVehicle = network->ODT[odt].vehicles->head; curVehicle !=
          NULL; curVehicle = curVehicle->next) {
183       deleteScalar(curVehicle->vehicle);
184     }
185     deleteVehicleDoublyLinkedList(network->ODT[odt].vehicles);
186     deletePathLinkedList(network->ODT[odt].paths);
187   }
188   deleteVehicleDoublyLinkedList(network->origin.cells->head->cell->
       vehicles);
189   deleteVehicleDoublyLinkedList(network->destination.cells->head->cell
       ->vehicles);
```

```
190   deleteScalar(network->origin.cells->head->cell);
191   deleteScalar(network->destination.cells->head->cell);
192   deleteCellDoublyLinkedList(network->origin.cells);
193   deleteCellDoublyLinkedList(network->destination.cells);
194   deleteVector(network->ODT);
195 }
196
197 /*
198 deleteNetwork -- Deallocates memory associated with the core data
       structures of a network
199 Arguments:
200    network -- pointer to a network_type containing all relevant
          parameters
201 */
202 void deleteNetwork(network_type *network) {
203   int i, ij;
204   turningLinkedListElt *curMovement;
205   pathLinkedListElt *curPath;
206
207   for (ij = 0; ij < network->numArcs; ij++) {
208     deleteTurningLinkedList(network->arc[ij].turnMovements);
209     deleteTurningLinkedList(network->arc[ij].upstreamMovements);
210   }
211
212   for (i = 0; i < network->numNodes; i++) {
213     switch (network->node[i].control) {
214       case TWO_WAY_STOP:
215          deletePriorityLinkedList(((twoWayStop_type *)(network->node[i
              ].controlData))->priorityList);
216          deleteScalar(network->node[i].controlData);
217          break;
218       case BASIC_SIGNAL:
219          deleteLinkedList(((basicSignal_type *)(network->node[i].
              controlData))->greenTime);
220          deleteScalar(network->node[i].controlData);
221          break;
222       case CENTROID:
223       case NONHOMOGENEOUS:
224       case DIVERGE:
225       case MERGE:
226       case FOUR_WAY_STOP:
227       case FANCY_SIGNAL:
228       case INTERCHANGE:
229       default: /* Simple intersection types do not require additional
          cleanup */
230          break;
231     }
```

```
232      deleteArcLinkedList(network->node[i].forwardStar);
233      deleteArcLinkedList(network->node[i].reverseStar);
234      for (curMovement = network->node[i].turnMovements->head;
             curMovement != NULL; curMovement = curMovement->next) {
235            deleteVehicleDoublyLinkedList(curMovement->movement->vehicles)
                 ;
236        deleteScalar(curMovement->movement);
237      }
238      deleteTurningLinkedList(network->node[i].turnMovements);
239    }
240
241     for (curPath = network->paths->head; curPath != NULL; curPath =
           curPath->next) {
242        deletePath(curPath->path);
243     }
244    deleteTurningLinkedList(network->origin.turnMovements);
245    deleteTurningLinkedList(network->destination.upstreamMovements);
246    deleteVector(network->arc);
247    deleteVector(network->node);
248    deletePathLinkedList(network->paths);
249    deleteMatrix(network->staticOD, network->numZones);
250     deleteScalar(network);
251  }
252
253  /*
254  initializeDTARun -- Read all files and allocate all memory needed for a
         run
255  Arguments:
256     run -- pointer to a parameters_type which will be initialized during
             this function
257     parametersFileName -- string with the name of the parameters file to
             read
258  */
259  void initializeDTARun(parameters_type *run,char *parametersFileName) {
260    int destination;
261    network_type *network = newScalar(network_type);
262    run->network = network;
263
264    readParametersFile(run, parametersFileName);
265
266    verbosity = run->verbosity;
267
268     initializeNetwork(run);
269    readNodeCoordinateFile(network, run->coordinateFileName);
270    readNodeControlFile(network, run->nodeControlFileName);
271
272     validateNetwork(network);
```

```
273   generateSchedule(network);
274   readDemandFile(run);
275
276   generateCells(network);
277   generateVehicles(network);
278   initializeCounts(network);
279
280   for (destination = 0; destination < network->numZones; destination++)
          {
281     calculateFreeFlowSPLabels(network, destination);
282   }
283
284   displayMessage(FULL_NOTIFICATIONS, "Finished initializing run.\n");
285 }
286
287 /*
288 initializeNetwork -- Read data from a network file, and initialize the
       relevnat network data structuer
289 Arguments:
290    run -- pointer to a parameters_type containing the network which
          will be initialized during this function.
291           This parameters_type contains the filename of the network
                file.
292 */
293 void initializeNetwork(parameters_type *run) {
294   int ij;
295   network_type *network = run->network;
296
297   network->numZones = IS_MISSING;
298   network->numArcs = IS_MISSING;
299   network->numNodes = IS_MISSING;
300   network->paths = createPathLinkedList();
301
302   network->sink.ID = 0;
303   network->origin.tail = &(network->sink);
304   network->origin.head = &(network->sink);
305   network->destination.head = &(network->sink);
306   network->destination.tail = &(network->sink);
307
308    readNetworkFile(network, run->networkFileName, run->
          backwardWaveRatio);
309    createStarLists(network);
310
311     network->tickLength = run->tickLength;
312   network->timeHorizon = ceil(run->timeHorizon / run->tickLength); /*
          Convert time horizon in seconds to clock ticks */
313   network->lastVehicleOn = ceil(run->lastVehicleOn / run->tickLength);
```

```
314
315   for (ij = 0; ij < network->numArcs; ij++) {
316     network->arc[ij].freeFlowToDest = newVector(network->numZones, int)
          ;
317     network->arc[ij].freeFlowMovement = newVector(network->numZones,
          turning_type *);
318   }
319
320 }
321
322 /**** Generate cell data structures ****/
323
324 /*
325 generateCells -- Create and allocate data structures related to cells
     in a network, partitioning each link into the
326                  right number of cells.
327 Arguments:
328    network -- pointer to a network_type to create cells for
329 */
330 void generateCells(network_type *network) {
331   int ij, c;
332   cell_type *newCell;
333
334   displayMessage(FULL_NOTIFICATIONS, "Generating cells...\n");
335
336   /* Create cells for artificial origin and destination links */
337   network->origin.cells = createCellDoublyLinkedList();
338   network->origin.numCells = 1;
339   network->origin.cellCapacity = INT_MAX;
340   network->origin.cellMaxVehicles = INT_MAX;
341   network->origin.waveRatio = 1;
342   newCell = newScalar(cell_type);
343   newCell->parentLink = &(network->origin);
344   newCell->vehicles = createVehicleDoublyLinkedList();
345   newCell->sendingFlow = 0;
346   newCell->receivingFlow = 0;
347   insertCellDoublyLinkedList(network->origin.cells, newCell, NULL);
348   network->destination.cells = createCellDoublyLinkedList();
349   network->destination.numCells = 1;
350   network->destination.cellCapacity = INT_MAX;
351   network->destination.cellMaxVehicles = INT_MAX;
352   network->destination.waveRatio = 1;
353   newCell = newScalar(cell_type);
354   newCell->parentLink = &(network->destination);
355   newCell->vehicles = createVehicleDoublyLinkedList();
356   newCell->sendingFlow = 0;
357   newCell->receivingFlow = 0;
```

```
358   insertCellDoublyLinkedList(network->destination.cells, newCell, NULL)
        ;
359
360   /* Create cells for all other links */
361   for (ij = 0; ij < network->numArcs; ij++) {
362     network->arc[ij].numCells = ceil(network->arc[ij].freeFlowTime /
          network->tickLength);
363     network->arc[ij].cellCapacity = ceil(network->arc[ij].capacity *
          network->tickLength);
364     network->arc[ij].cellMaxVehicles = ceil(network->arc[ij].length *
          network->arc[ij].jamDensity / network->arc[ij].numCells);
365     network->arc[ij].cells = createCellDoublyLinkedList();
366     for (c = 0; c < network->arc[ij].numCells; c++) {
367       newCell = newScalar(cell_type);
368       newCell->parentLink = &(network->arc[ij]);
369       newCell->vehicles = createVehicleDoublyLinkedList();
370       newCell->sendingFlow = 0;
371       newCell->receivingFlow = 0;
372       insertCellDoublyLinkedList(network->arc[ij].cells, newCell,
            network->arc[ij].cells->tail);
373     }
374   }
375
376   displayMessage(FULL_NOTIFICATIONS, "done.\n");
377 }
378
379 /**** Network validation ****/
380
381 /*
382 validateNetwork -- Ensure that the network is valid: node control is
      appropriate based on number of
383                    incoming and outgoing links; no duplicate turn
                         movements listed; network is
384                    properly connected, each destination is reachable
                         from each origin.
385 Arguments:
386    network -- pointer to a network_type for validation
387 */
388 void validateNetwork(network_type *network) {
389   displayMessage(MEDIUM_NOTIFICATIONS, "Validating network data...\n");
390
391   validateNodeControl(network);
392   checkDuplicateTurnMovements(network);
393   checkNetworkConnectivity(network);
394
395   displayMessage(MEDIUM_NOTIFICATIONS, "...validation complete.\n");
396 }
```

```
397
398 /*
399 validateNodeControl -- Check that each node's assigned control is
       compatible with the number of
400                        entering and leaving links.
401 Arguments:
402    network -- pointer to a network_type for validation
403 */
404 void validateNodeControl(network_type *network) {
405   int i;
406
407   displayMessage(FULL_NOTIFICATIONS, "Checking node control...\n");
408
409   /* Confirm all nodes have a relevant control file entry and finite
       tick length */
410   for (i = 0; i < network->numNodes; i++) {
411     if (network->node[i].control == UNKNOWN_CONTROL) fatalError("Node %
         d either missing in node control file, or unknown control type."
         , i+1);
412   }
413
414   /* Check turning movement compatability with control types (not more
       than one into a diverge, not more than one out of a merge, etc.)
       */
415   for (i = 0; i < network->numNodes; i++) {
416     if (i < network->numZones && network->node[i].control != CENTROID)
         warning(FULL_NOTIFICATIONS, "Origin/destination %d does not have
          CENTROID control.", i+1);
417     switch (network->node[i].control) {
418     case CENTROID:
419       if (i > network->numZones) warning(FULL_NOTIFICATIONS, "Centroid
           node type found for node %d which is neither an origin nor a
           destination.", i+1
420       );
421       if (network->node[i].reverseStar->size == 0) warning(
           FULL_NOTIFICATIONS, "No incoming links for centroid %d\n", i
           +1);
422       if (network->node[i].forwardStar->size == 0) warning(
           FULL_NOTIFICATIONS, "No outgoing links for centroid %d\n", i
           +1);
423       break;
424     case NONHOMOGENEOUS:
425       if (network->node[i].reverseStar->size > 1) fatalError("
           Nonhomogeneous node %d has more than one incoming link!", i+1)
           ;
426       if (network->node[i].forwardStar->size > 1) fatalError("
           Nonhomogeneous node %d has more than one outgoing link!", i+1)
```

```
          ;
427       if (network->node[i].turnMovements->size == 0) fatalError("No
             turning movements listed for non-centroid node %d", i+1);
428       break;
429     case MERGE:
430       if (network->node[i].reverseStar->size <= 1) fatalError("Merge
             node %d needs at least two incoming links!", i+1);
431       if (network->node[i].forwardStar->size != 1) fatalError("Merge
             node %d has more than one outgoing link!", i+1);
432       if (network->node[i].turnMovements->size == 0) fatalError("No
             turning movements listed for non-centroid node %d", i+1);
433       break;
434     case DIVERGE:
435       if (network->node[i].reverseStar->size != 1) fatalError("Diverge
             node %d has more than one incoming link!", i+1);
436       if (network->node[i].forwardStar->size <= 1) fatalError("Diverge
             node %d needs at least two outgoing links!", i+1);
437       if (network->node[i].turnMovements->size == 0) fatalError("No
             turning movements listed for non-centroid node %d", i+1);
438       break;
439     case TWO_WAY_STOP:
440     case FOUR_WAY_STOP:
441     case BASIC_SIGNAL:
442     case INTERCHANGE:
443         if (network->node[i].reverseStar->size == 0) fatalError("No
               incoming links for non-centroid node %d\n", i+1);
444       if (network->node[i].forwardStar->size == 0) fatalError("No
             outgoing links for non-centroid node %d\n", i+1);
445         break;
446     case FANCY_SIGNAL:
447       warning(LOW_NOTIFICATIONS, "Not all node control types have error
              checking implemented, skipping node %d.\n", i+1);
448         break;
449     case UNKNOWN_CONTROL:
450     default:
451       fatalError("Unknown or missing node control type for node %d.", i
             +1);
452     }
453   }
454
455   displayMessage(FULL_NOTIFICATIONS, "...done.\n");
456 }
457
458 /*
459 checkDuplicateTurnMovements -- Ensure that no turn movement is listed
       multiple times in a network.
460 Arguments:
```

```
461     network -- pointer to a network_type for validation
462  */
463  void checkDuplicateTurnMovements(network_type *network) {
464    int i;
465    long curHash, compareHash;
466    turningLinkedListElt *curMovementElt, *compareMovementElt;
467    turning_type *curMovement, *compareMovement;
468
469    displayMessage(FULL_NOTIFICATIONS, "Checking for duplicate turning
         movements...\n");
470    for (i = 0; i < network->numNodes; i++) {
471      for (curMovementElt = network->node[i].turnMovements->head;
           curMovementElt != NULL; curMovementElt = curMovementElt->next) {
472        curMovement = curMovementElt->movement;
473        curHash = ptr2arc(network, curMovement->upstreamArc) * network->
             numArcs + ptr2arc(network, curMovement->downstreamArc);
474        for (compareMovementElt = curMovementElt->next;
             compareMovementElt != NULL; compareMovementElt =
             compareMovementElt->next) {
475          compareMovement = compareMovementElt->movement;
476          compareHash = ptr2arc(network, compareMovement->upstreamArc) *
               network->numArcs + ptr2arc(network, compareMovement->
               downstreamArc);
477          if (curHash == compareHash) fatalError("Duplicate turning
               movements for node %d", i+1);
478        }
479      }
480    }
481
482    displayMessage(FULL_NOTIFICATIONS, "done.\n");
483  }
484
485  /**** Network data structure creation ****/
486
487  /*
488  generateSchedule -- Dimension and allocate memory for all time-related
       objects
489  Arguments:
490     network -- pointer to the relevant network_type
491  */
492  void generateSchedule(network_type *network) {
493    int i, ij;
494    turningLinkedListElt *curMovement;
495
496    /* Dimension turning movements */
497    for (i = 0; i < network->numNodes; i++) {
498      for (curMovement = network->node[i].turnMovements->head;
```

```
          curMovement != NULL; curMovement = curMovement->next) {
499       curMovement->movement->travelTime = newVector(network->
             timeHorizon, int);
500       curMovement->movement->upstreamCount = newVector(network->
             timeHorizon, int);
501       curMovement->movement->downstreamCount = newVector(network->
             timeHorizon, int);
502     }
503   }
504
505   /* Dimension all links */
506   for (ij = 0; ij < network->numArcs; ij++) {
507     network->arc[ij].travelTime = newVector(network->timeHorizon, int);
508     network->arc[ij].upstreamCount = newVector(network->timeHorizon,
          int);
509     network->arc[ij].downstreamCount = newVector(network->timeHorizon,
          int);
510   }
511    network->origin.travelTime = newVector(network->timeHorizon, int);
512    network->origin.upstreamCount = newVector(network->timeHorizon, int)
         ;
513    network->origin.downstreamCount = newVector(network->timeHorizon,
         int);
514    network->destination.travelTime = newVector(network->timeHorizon,
         int);
515    network->destination.upstreamCount = newVector(network->timeHorizon,
          int);
516    network->destination.downstreamCount = newVector(network->
         timeHorizon, int);
517 }
518
519 /*
520 profileDemand -- Determine the number of vehicles departing in each
      time interval;
521                  create the ODT array, which is sorted by time.  This
                        makes it faster to
522                  load vehicles during simulation.
523 Arguments:
524    thisRun -- pointer to the parameters_type with all run parameters (
         including profile type
525               and relevant parameters)
526 */
527 void profileDemand(parameters_type *thisRun) {
528   long r, s, t, odt = 0;
529   long numODTs = 0, newVehicles, numVehicles = 0;
530   network_type *network = thisRun->network;
531   declareVector(float, proportion, network->timeHorizon);
```

```
532   declareVector(float, demand, network->timeHorizon);
533
534   /* Identify demand profile */
535   switch (thisRun->demandProfile) {
536   case UNIFORM_PROFILE:
537     profileDemandUniform(proportion, network->lastVehicleOn, network->
          timeHorizon);
538     break;
539    case TRIANGLE:
540       profileDemandTriangle(proportion, network, (triangleProfile_type
           *)(thisRun->profileParameters));
541       break;
542   case PEAK:
543   case QUADRATIC:
544     fatalError("Selected demand profile type not yet implemented.");
545    case RAW:
546       fatalError("Code should call readRawODTFile for RAW profiles, not
           profileDemand.");
547   default:
548     fatalError("Unknown demand profile type %d.", thisRun->
          demandProfile);
549   }
550
551   /* Determine amount of demand in each time interval */
552   srand(thisRun->randomSeed);
553   for (t = 0; t < network->timeHorizon; t++) {
554      displayMessage(DEBUG, "Demand proportion in time interval %d is %f
          \n", t, proportion[t]);
555     for (r = 0; r < network->numZones; r++) {
556     network->staticOD[r][r] = 0;
557       for (s = 0; s < network->numZones; s++) {
558         demand[t] = network->staticOD[r][s] * proportion[t];
559         newVehicles = stochasticRound(demand[t]);
560         if (newVehicles > 0) {
561           numVehicles += newVehicles;
562           numODTs++;
563         }
564       }
565     }
566   }
567   network->numVehicles = numVehicles;
568   network->numODTs = numODTs;
569   network->ODT = newVector(numODTs, ODT_type);
570
571   /* Make second pass through OD table to generate vehicles as needed.
        (Doing passes separately to save memory, must re-seed RNG) */
572   srand(thisRun->randomSeed);
```

```
573   for (t = 0; t < network->timeHorizon; t++) {
574     for (r = 0; r < network->numZones; r++) {
575       for (s = 0; s < network->numZones; s++) {
576         demand[t] = network->staticOD[r][s] * proportion[t];
577         newVehicles = stochasticRound(demand[t]);
578         if (newVehicles > 0) {
579           network->ODT[odt].origin = &(network->node[r]);
580           network->ODT[odt].destination = &(network->node[s]);
581           network->ODT[odt].departureTime = t;
582           network->ODT[odt].demand = newVehicles;
583           network->ODT[odt].vehicles = createVehicleDoublyLinkedList();
584           network->ODT[odt].paths = createPathLinkedList();
585           odt++;
586         }
587       }
588     }
589   }
590 
591   deleteVector(proportion);
592   deleteVector(demand);
593 }
594 
595 /*
596 profileDemandUniform -- generate a "uniform" proportions array, evenly
       distributed over the time horizon
597 Arguments:
598    proportion -- array of floats which will be filled by this function
599    lastVehicleOn -- last time interval where demand will be loaded
600    timeHorizon -- upper bound for all time-dimensioned arrays
601 */
602 void profileDemandUniform(float *proportion, int lastVehicleOn, int
       timeHorizon) {
603   int t;
604    fillLinearProfileDemand(proportion, 0, lastVehicleOn, 1, 1);
605   for (t = lastVehicleOn; t < timeHorizon; t++) {
606     proportion[t] = 0;
607   }
608 }
609 
610 /*
611 fillLinearProfileDemand -- fill a (subset of a) proportions array with
       proportions that change linearly with time
612 Arguments:
613    proportion -- array of floats which will be filled by this function
614    firstVehicleOn -- first time interval to fill in
615    lastVehicleOn -- last time interval to fill in
616    firstLastRatio -- ratio between demand at the last interval and
```

```
        first interval (>1 for increasing, =1 for constant, <1 for
        decreasing)
617     totalProportion -- total proportion to assign between first and last
         intervals (1 for all demand, 1/2 for half of total demand, etc.)
618 */
619 void fillLinearProfileDemand(float *proportion, int firstVehicleOn, int
     lastVehicleOn, float firstLastRatio, float totalProportion) {
620     int t = firstVehicleOn;
621     float base = 2 / ((lastVehicleOn - firstVehicleOn) * (1 +
        firstLastRatio)) * totalProportion;
622     float slope = base * (firstLastRatio - 1) / (lastVehicleOn -
        firstVehicleOn - 1);
623
624     if (firstLastRatio < 0) fatalError("fillLinearprofileDemand:
        firstLastRatio must be nonnegative!");
625     if (firstVehicleOn > lastVehicleOn) fatalError("
        fillLinearProfileDemand: firstVehicleOn must be no greater than
        lastVehicleOn");
626
627     displayMessage(FULL_DEBUG, "Drawing line with base %f and slope %f
        from %d to %d\n", base, slope, firstVehicleOn, lastVehicleOn);
628
629     proportion[t++] = base;
630     for (; t < lastVehicleOn; t++) {
631        proportion[t] = proportion[t - 1] + slope;
632     }
633 }
634
635 /*
636 profileDemandTriangle -- generate a "triangular" proportions array, as
       specified by the arguments
637 Arguments:
638     proportion -- array of floats which will be filled by this function
639     network -- pointer to a network_type containing tick length (needed
        to convert peak time, which is in external units, to simulation
        time intervals)
640     parameters -- pointer to a triangleProfile_type containing relevant
        data for the triangle profile (ratios, peak time, etc.)
641 */
642 void profileDemandTriangle(float *proportion, network_type *network,
       triangleProfile_type *parameters) {
643   int t;
644   float a, b, c; /* Demand levels at initial, peak, and final time
        intervals */
645   int lastVehicleOn = network->lastVehicleOn;
646   int timeHorizon = network->timeHorizon;
647   int peakTime = ceil(parameters->peakTime / network->tickLength);
```

```
648    float firstRatio = parameters->ratio1, lastRatio = parameters->ratio2
          ;
649
650    /* Validate data */
651    if (peakTime > lastVehicleOn || peakTime < 0) fatalError("TRIANGLE
          profile: peak demand time interval %d is out of range (raw time %f
          )\n", peakTime, parameters->peakTime);
652    if (firstRatio < 0 || lastRatio < 0) fatalError("TRIANGLE profile:
          ratios 1 and 2 must be nonnegative.\n");
653
654    /* Convert into proper format */
655
656    a = 2 / (peakTime * (1 + firstRatio) + (lastVehicleOn - peakTime + 1)
           * firstRatio * (1 + lastRatio) - 2 * firstRatio);
657    b = a * firstRatio;
658    c = b * lastRatio;
659    displayMessage(FULL_DEBUG, "Triangle parameters a=%f b=%f c=%f\n", a,
           b, c);
660    displayMessage(FULL_DEBUG, "Drawing lines with total proportion %f
          and %f\n", peakTime * (a+b)/2,  (lastVehicleOn - peakTime + 1) * (
          b + c) / 2);
661    fillLinearProfileDemand(proportion, 0, peakTime, firstRatio, peakTime
           * (a + b) / 2);
662    fillLinearProfileDemand(proportion, peakTime - 1, lastVehicleOn,
          lastRatio, (lastVehicleOn - peakTime + 1) * (b + c) / 2);
663    for (t = lastVehicleOn; t < timeHorizon; t++) {
664      proportion[t] = 0;
665    }
666 }
```

D.1.4 dta.h

```
1  #ifndef _DTA_H_
2  #define _DTA_H_
3
4  #include <math.h>
5  #include <stdlib.h>
6  #include <time.h>
7  #include "datastructures.h"
8  #include "fileio.h"
9  #include "network.h"
10 #include "node.h"
11 #include "sampling.h"
12 #include "utils.h"
13 #include "vehicle.h"
14
15 typedef enum {
```

```
16    UNKNOWN_PROFILE,
17    UNIFORM_PROFILE, /* UNIFORM clashes with sampling.h's UNIFORM
         distribution */
18    TRIANGLE,
19    QUADRATIC,
20    PEAK,
21    RAW
22  } profile_enum;
23
24  typedef enum {
25    MSA,
26    LUCE
27  } algorithm_enum;
28
29  typedef struct parameters_type_s {
30     char           networkFileName[STRING_SIZE];
31     char           demandFileName[STRING_SIZE];
32     char           coordinateFileName[STRING_SIZE];
33     char           nodeControlFileName[STRING_SIZE];
34     char           countsFileName[STRING_SIZE];
35     char           linkSummaryName[STRING_SIZE];
36     char           nodeSummaryName[STRING_SIZE];
37     char           graphicsFileName[STRING_SIZE];
38     profile_enum demandProfile;
39     void           *profileParameters;  /* Additional optional
          parameters for different profile types */
40     network_type   *network;
41     algorithm_enum solutionAlgorithm;
42     long           timeHorizon;         /* End of simulation, in *
          seconds*                */
43     long           warmUpLength;        /* Warm-up period, in *seconds*
          (for summaries)       */
44     long           coolDownLength;      /* Cool-down period, in *seconds
          * (for summaries)     */
45     long           lastVehicleOn;       /* Time last vehicle enters the
          network, in *seconds* */
46     float          maxRunTime;          /* Seconds
                                                  */
47     int        maxIterations;
48     float          AECtarget;           /* Average excess cost
          termination level           */
49     float        vehicleLength;       /* Feet
                                                 */
50     float        demandMultiplier;
51     float          tickLength;
52     float        backwardWaveRatio;
53    int       verbosity;
```

```
54   int       randomSeed;
55 } parameters_type ;
56
57 typedef struct triangleProfile_type_s {
58    long           peakTime;
59    float          ratio1;
60    float          ratio2;
61 } triangleProfile_type;
62
63 /**** Core DTA routines ****/
64
65 void DTA(parameters_type *run);
66 void simulateCTM(network_type *network);
67 void shiftMSA(network_type *network, float movingFraction);
68 void cleanUpDTARun(parameters_type *run);
69 void deleteSchedule(network_type *network);
70 void deleteNetwork(network_type *network);
71
72 void initializeDTARun(parameters_type *run,char *parametersFileName);
73 void initializeNetwork(parameters_type *run);
74 void generateCells(network_type *network);
75
76 /**** Network validation ****/
77
78 void validateNetwork(network_type *network);
79 void validateNodeControl(network_type *network);
80 void checkDuplicateTurnMovements(network_type *network);
81
82 /**** Network data structure creation ****/
83
84 void generateSchedule(network_type *network);
85
86 /**** Demand profiling ****/
87
88 void profileDemand(parameters_type *thisRun);
89 void profileDemandUniform(float *proportion, int lastVehicleOn, int
      timeHorizon);
90 void fillLinearProfileDemand(float *proportion, int firstVehicleOn, int
       lastVehicleOn, float firstLastRatio, float totalProportion);
91 void profileDemandTriangle(float *proportion, network_type *network,
      triangleProfile_type *parameters);
92
93 #endif
```

D.1.5 fileio.c

```
1 #include  "fileio.h"
```

```
2
3  /*********************
4   ** File processing **
5   *********************/
6
7  /*
8  openFile -- wrapper for the library fopen function with error checking
9  Arguments:
10    filename -- name of file to open
11    access -- access mode for opening (same syntax as fopen)
12 */
13 FILE *openFile(char *filename, char *access) {
14   FILE *handle = fopen(filename, access);
15   if (handle == NULL) fatalError("File %s not found", filename);
16   return handle;
17 }
18
19 /*************************
20  ** Reading network files **
21  *************************/
22
23 /* Assumptions:
24   All input data is in units of miles/hour; program converts to
        internal units
25 */
26
27 /*
28 readNetworkFile -- reads a text network file for use in simulation
29 Arguments:
30    network -- pointer to network_type to read in
31    networkFileName -- name of network file
32    backwardWaveRatio -- default delta value to use; typically set in
        parameters file
33 */
34 void readNetworkFile(network_type *network, char *networkFileName,
      float backwardWaveRatio) {
35   int i, j;
36   int numParams, status;
37
38   char fullLine[STRING_SIZE], trimmedLine[STRING_SIZE];
39   char metadataTag[STRING_SIZE], metadataValue[STRING_SIZE];
40
41   FILE *linkFile = openFile(networkFileName, "r");
42
43   bool endofMetadata = FALSE;
44   float speedLimit;
45   char checkChar;
```

```
46    int tail, head;
47
48    /* Read link file metadata */
49    do {
50      if (fgets(fullLine, STRING_SIZE, linkFile) == NULL) fatalError("
          Network file %s ended before metadata complete.",
          networkFileName);
51      status = parseMetadata(fullLine, metadataTag, metadataValue);
52      if (status == BLANK_LINE || status == COMMENT) continue;
53      if          (strcmp(metadataTag, "NUMBER OF ZONES") == 0) {
54        network->numZones = atoi(metadataValue);
55      } else if (strcmp(metadataTag, "NUMBER OF LINKS") == 0) {
56        network->numArcs = atoi(metadataValue);
57      } else if (strcmp(metadataTag, "NUMBER OF NODES") == 0) {
58        network->numNodes = atoi(metadataValue);
59      } else if (strcmp(metadataTag, "END OF METADATA") == 0) {
60        endofMetadata = TRUE;
61      } else {
62        warning(MEDIUM_NOTIFICATIONS, "Ignoring unknown metadata tag %s
            in parameters file %s\n", metadataTag, networkFileName);
63      }
64    } while (endofMetadata == FALSE);
65
66    /* Check input for completeness and correctness */
67    if (network->numZones == IS_MISSING) fatalError("Link file %s does
        not contain number of zones.", networkFileName);
68    if (network->numNodes == IS_MISSING) fatalError("Link file %s does
        not contain number of nodes.", networkFileName);
69    if (network->numArcs == IS_MISSING)  fatalError("Link file %s does
        not contain number of links.", networkFileName);
70    if (network->numZones < 1) fatalError("Link file %s does not contain
        a positive number of nodes.", networkFileName);
71    if (network->numArcs < 1) fatalError("Link file %s does not contain a
         positive number of links.",  networkFileName);
72    if (network->numNodes < 1) fatalError("Link file %s does not contain
        a positive number of nodes.", networkFileName);
73
74    network->node = newVector(network->numNodes, node_type);
75    network->arc = newVector(network->numArcs, arc_type);
76    network->staticOD = newMatrix(network->numZones, network->numZones,
        float);
77
78    for (i = 0; i < network->numNodes; i++) {
79      network->node[i].ID = i + 1;
80    }
81
82    for (i = 0; i < network->numZones; i++) {
```

```
83      for (j = 0; j < network->numZones; j++) {
84        network->staticOD[i][j] = 0;
85      }
86    }
87
88    /* Read link data */
89    for (i = 0; i < network->numArcs; i++) {
90      do {
91        if (fgets(fullLine, STRING_SIZE, linkFile) == NULL) fatalError("
             Link file %s ended before link data complete.",
             networkFileName);
92        status = parseLine(fullLine, trimmedLine);
93      } while (status == BLANK_LINE || status == COMMENT);
94      numParams = sscanf(trimmedLine,"%d %d %f %f %f %f %c",
95        &tail,
96        &head,
97        &network->arc[i].capacity,
98        &network->arc[i].length,
99        &speedLimit,
100       &network->arc[i].jamDensity,
101       &checkChar);
102     if (numParams != 7 || checkChar != ';') fatalError("Link file %s
          has an error in this line:\n %s", networkFileName, fullLine);
103     if (tail < 1 || tail > network->numNodes) fatalError("Arc tail %d
          out of range in network file %s.", i, networkFileName);
104     if (head < 1 || head > network->numNodes) fatalError("Arc head %d
          out of range in network file %s.", i, networkFileName);
105     /* Create links to data structures */
106     network->arc[i].ID = i + 1;
107     network->arc[i].tail = &(network->node[tail-1]);
108     network->arc[i].head = &(network->node[head-1]);
109     /* Convert units to internal units.  Multiply by units in the
          numerator, divide by units in the denominator.  Unit definitions
           in dta.h */
110     network->arc[i].length *= FEET;
111     network->arc[i].capacity /= HOURS;
112     speedLimit *= MILES / HOURS;
113     network->arc[i].jamDensity /= MILES;
114     /* Check for plausibility assuming trapezoidal fundamental diagram
          */
115     if (network->arc[i].length < 0) fatalError("Arc length %d negative
          in network file %s.\n%s", i+1, networkFileName, fullLine);
116     if (speedLimit <= 0) fatalError("Arc speed limit %d nonpositive in
          network file %s.\n%s", i+1, networkFileName, fullLine);
117     if (network->arc[i].capacity <= 0) fatalError("Capacity %d
          nonpositive in network file %s.\n%s", i+1, networkFileName,
          fullLine);
```

```
118      if (network->arc[i].jamDensity <= 0) fatalError("Jam density %d
            nonpositive in network file %s.\n%s", i+1, networkFileName,
            fullLine);
119      /* if (network->arc[i].jamDensity <= network->arc[i].capacity /
            speedLimit) warning(FULL_NOTIFICATIONS, "Arc jam density %d too
            small to be consistent with specified capacity and speed in
            network file %s.\n%s\nFundamental diagram for this link will be
            triangular, not trapezoidal.\n", i+1, networkFileName, fullLine)
            ; */
120      network->arc[i].freeFlowTime = network->arc[i].length / speedLimit;
121      network->arc[i].waveRatio = backwardWaveRatio;
122    }
123
124    fclose(linkFile);
125    displayMessage(MEDIUM_NOTIFICATIONS, "Network has %d nodes, %d arcs,
          and %d zones\n", network->numNodes, network->numArcs, network->
          numZones);
126    displayMessage(LOW_NOTIFICATIONS, "Network file read and memory
          allocated.\n");
127  }
128
129  /*
130  readDemandFile -- detects whether demand type is RAW or based on a
       profile, and calls the appropriate function
131  Arguments:
132     run -- pointer to parameters_type specifying demand type
133  */
134  void readDemandFile(parameters_type *run) {
135     if (run->demandProfile == RAW) {
136        readRawODTFile(run->network, run->demandFileName, &(run->
              demandMultiplier));
137     } else {
138        readStaticODFile(run->network, run->demandFileName, &(run->
              demandMultiplier));
139        profileDemand(run);
140     }
141  }
142
143  /*
144  readRawODTFile -- reads a demand file in the RAW format.  As a general
       caution: these files only work with a particular time
145                  discretization.  The time index is a time *interval*,
                         not a "real" time value
146  Arguments:
147     network -- pointer to network_type which will contain demand
148     rawODTFileName -- name of RAW demand file
149     demandMultiplier -- constant factor for scaling demand.  Can be
```

```
        provided in parameters file or in demand file
150 */
151 void readRawODTFile(network_type *network, char *rawODTFileName, float
       *demandMultiplier) {
152    int orig, dest, t, odt, numVehicles, numODTs = IS_MISSING;
153    int numParams, status, check;
154    char fullLine[STRING_SIZE], trimmedLine[STRING_SIZE];
155    char metadataTag[STRING_SIZE], metadataValue[STRING_SIZE];
156    float rawDemand, totalDemandCheck = 0, totalODFlow = IS_MISSING;
157    bool endofMetadata = FALSE;
158    FILE *rawODTFile = openFile(rawODTFileName, "r");
159
160   do {
161     if (fgets(fullLine, STRING_SIZE, rawODTFile) == NULL) fatalError("
          Raw ODT file %s ended before metadata complete.", rawODTFileName
          );
162     status = parseMetadata(fullLine, metadataTag, metadataValue);
163     if (status == BLANK_LINE || status == COMMENT) continue;
164     if          (strcmp(metadataTag, "NUMBER OF ZONES") == 0) {
165       check = atoi(metadataValue);
166       if (check != network->numZones) fatalError("Number of zones in
            network file and raw ODT file do not match.");
167     } else if (strcmp(metadataTag, "TOTAL OD FLOW") == 0) {
168       totalODFlow = atof(metadataValue);
169     } else if (strcmp(metadataTag, "DEMAND MULTIPLIER") == 0) {
170       *demandMultiplier = atof(metadataValue);
171     } else if (strcmp(metadataTag, "NUMBER OF ODTS") == 0) {
172          numODTs = atoi(metadataValue);
173     } else if (strcmp(metadataTag, "END OF METADATA") == 0) {
174       endofMetadata = TRUE;
175     } else {
176       warning(MEDIUM_NOTIFICATIONS, "Ignoring unknown metadata tag %s
            in trips file %s\n", metadataTag, rawODTFileName);
177     }
178   } while (endofMetadata == FALSE);
179   network->numODTs = numODTs;
180   network->ODT = newVector(numODTs, ODT_type);
181
182   for (odt = 0; odt < numODTs; odt++) {
183     do {
184       if (fgets(fullLine, STRING_SIZE, rawODTFile) == NULL) fatalError(
            "Raw ODT file %s ended before ODT data complete.",
            rawODTFileName);
185       status = parseLine(fullLine, trimmedLine);
186     } while (status == BLANK_LINE || status == COMMENT);
187     numParams = sscanf(trimmedLine,"%d %d %d %f", &orig, &dest, &t, &
          rawDemand);
```

```
188      if (numParams != 4) fatalError("Raw ODT file has an error in this
            line:\n%s", fullLine);
189      if (orig < 1 || orig > network->numZones) fatalError("Origin zone %
            d out of range in raw ODT file.", orig);
190      if (dest < 1 || dest > network->numZones) fatalError("Destination
            zone %d out of range in raw ODT file.", dest);
191      if (t < 0 || t > network->lastVehicleOn) fatalError("Departure time
             %d out of range [0, %d] in raw ODT file.", t, network->
            lastVehicleOn);
192        if (rawDemand < 0) fatalError("Number of vehicles for ODT %d -> %
              d @ %d must be nonnegative in raw ODT file.", orig, dest, t);
193        network->ODT[odt].origin = &(network->node[orig-1]);
194        network->ODT[odt].destination = &(network->node[dest-1]);
195        network->ODT[odt].departureTime = t;
196        numVehicles = stochasticRound(rawDemand * *demandMultiplier);
197        network->ODT[odt].demand = numVehicles;
198        network->ODT[odt].vehicles = createVehicleDoublyLinkedList();
199        network->ODT[odt].paths = createPathLinkedList();
200        totalDemandCheck += rawDemand;
201    }
202
203    if (totalODFlow != IS_MISSING) displayMessage(FULL_NOTIFICATIONS, "
          Total demand %f compared to metadata %f\n", totalDemandCheck,
          totalODFlow);
204     network->totalODFlow = totalDemandCheck * *demandMultiplier;
205     fclose(rawODTFile);
206     displayMessage(LOW_NOTIFICATIONS, "Trip table read.\n");
207
208 }
209
210 /*
211 readStaticODFile -- reads a demand matrix file
212 Arguments:
213    network -- pointer to network_type which will contain demand
214    staticODFileName -- name of demand matrix file
215    demandMultiplier -- constant factor for scaling demand.  Can be
          provided in parameters file or in demand file
216 */
217 void readStaticODFile(network_type *network, char *staticODFileName,
       float *demandMultiplier) {
218    int i, j;
219    int numParams, status, check;
220    double demand, totalDemandCheck = 0;
221
222    char fullLine[STRING_SIZE], trimmedLine[STRING_SIZE], *token;
223    char metadataTag[STRING_SIZE], metadataValue[STRING_SIZE];
224
```

```
225   bool endofMetadata = FALSE;
226   double totalODFlow = IS_MISSING;
227
228   FILE *tripFile = openFile(staticODFileName, "r");
229
230   /* Verify trip table metadata */
231   do {
232     if (fgets(fullLine, STRING_SIZE, tripFile) == NULL) fatalError("
          Trips file %s ended before metadata complete.", staticODFileName
          );
233     status = parseMetadata(fullLine, metadataTag, metadataValue);
234     if (status == BLANK_LINE || status == COMMENT) continue;
235     if         (strcmp(metadataTag, "NUMBER OF ZONES") == 0) {
236       check = atoi(metadataValue);
237       if (check != network->numZones) fatalError("Number of zones in
            trip and link files do not match.");
238     } else if (strcmp(metadataTag, "TOTAL OD FLOW") == 0) {
239       totalODFlow = atof(metadataValue);
240     } else if (strcmp(metadataTag, "DEMAND MULTIPLIER") == 0) {
241       *demandMultiplier = atof(metadataValue);
242     } else if (strcmp(metadataTag, "END OF METADATA") == 0) {
243       endofMetadata = TRUE;
244     } else {
245       warning(MEDIUM_NOTIFICATIONS, "Ignoring unknown metadata tag %s
            in trips file %s\n", metadataTag, staticODFileName);
246     }
247   } while (endofMetadata == FALSE);
248
249   /* Now read trip table */
250   while (!feof(tripFile)) {
251     if (fgets(fullLine, STRING_SIZE, tripFile) == NULL) break;
252     status = parseLine(fullLine, trimmedLine);
253     if (status == BLANK_LINE || status == COMMENT || feof(tripFile))
          continue;
254     if (strstr(trimmedLine, "Origin") != NULL) {
255       sscanf(strstr(trimmedLine, "Origin")+6,"%d", &i);  /* i indexes
            current origin */
256       if (i < 1 || i > network->numNodes) fatalError("Origin %d is out
            of range in trips file %s", j, staticODFileName);
257       continue;
258     }
259     token = strtok(trimmedLine , ";");
260     while (token != NULL && strlen(token) > 1) {
261       numParams = sscanf(token, "%d : %lf", &j, &demand);
262       if (j < 1 || j > network->numNodes) fatalError("Destination %d is
            out of range in trips file %s\n%s\n%s", j, staticODFileName,
            fullLine, token);
```

```
263         if (numParams < 2) break;
264         network->staticOD[i-1][j-1] = demand * *demandMultiplier;
265         if (demand < 0) fatalError("Negative demand from origin %d to
               destination %d", i, j);
266         totalDemandCheck += network->staticOD[i-1][j-1];
267         token = strtok(NULL, ";");
268       }
269       blankInputString(trimmedLine, STRING_SIZE);
270     }
271
272     if (totalODFlow != IS_MISSING) displayMessage(FULL_NOTIFICATIONS, "
          Total demand %f compared to metadata %f\n", totalDemandCheck,
          totalODFlow);
273     /* Regardless of the 'check' value, update the network totalODFlow to
           the true value */
274     network->totalODFlow = totalDemandCheck * *demandMultiplier;
275     fclose(tripFile);
276
277      displayMessage(LOW_NOTIFICATIONS, "Trip table read.\n");
278
279 }
280
281 /*
282 readNodeCoordinateFile -- reads the node data file
283 Arguments:
284    network -- pointer to network_type which contains nodes
285    coordinateFileName -- name of node coordinates file
286 */
287 void readNodeCoordinateFile(network_type *network, char *
       coordinateFileName) {
288     int status;
289     char fullLine[STRING_SIZE], trimmedLine[STRING_SIZE];
290     float tempX, tempY;
291
292     FILE *coordinateFile = openFile(coordinateFileName, "r");
293
294     int i;
295     for (i = 0; i < network->numNodes; i++) {
296       network->node[i].X = INFINITY;
297       network->node[i].Y = INFINITY;
298     }
299
300     while (!feof(coordinateFile)) {
301       if (fgets(fullLine, STRING_SIZE, coordinateFile) == NULL) break;
302       status = parseLine(fullLine, trimmedLine);
303       if (status == BLANK_LINE || status == COMMENT || feof(
             coordinateFile)) continue;
```

```
304       sscanf(trimmedLine, "%d %f %f", &i, &tempX, &tempY);
305       if (i < 1 || i > network->numNodes) {
306         warning(MEDIUM_NOTIFICATIONS, "Node %d out of range in
              coordinates file, skipping.\n", i);
307         continue;
308       }
309       network->node[i-1].X = tempX;
310       network->node[i-1].Y = tempY;
311     }
312
313     for (i = 0; i < network->numNodes; i++) {
314       if (network->node[i].X == INFINITY || network->node[i].Y ==
            INFINITY) {
315         fatalError("No coordinates found for node %d\n", i+1);
316       }
317     }
318     fclose(coordinateFile);
319
320     displayMessage(FULL_NOTIFICATIONS, "Finished reading node coordinate
          file.\n");
321 }
322
323 /*
324 readNodeControlFile -- reads an intersection control file
325 Arguments:
326    network -- pointer to network_type which will contain node control
327    nodeControlFileName -- name of intersection control file
328 */
329 void readNodeControlFile(network_type *network, char *
       nodeControlFileName) {
330     int curNode = IS_MISSING;
331     int i, status;
332     arcLinkedListElt *curArc;
333     char fullLine[STRING_SIZE], trimmedLine[STRING_SIZE], controlText[
          STRING_SIZE];
334     twoWayStop_type *twoWayStopControl;
335     turning_type *newTurningMovement;
336     basicSignal_type *basicSignalControl;
337
338     FILE *nodeControlFile = openFile(nodeControlFileName, "r");
339     for (i = 0; i < network->numNodes; i++) {
340       network->node[i].turnMovements = createTurningLinkedList();
341       network->node[i].control = UNKNOWN_CONTROL;
342     }
343     for (i = 0; i < network->numArcs; i++) {
344       network->arc[i].turnMovements = createTurningLinkedList();
345       network->arc[i].upstreamMovements = createTurningLinkedList();
```

```
346   }
347
348   /* Create turn movements for each origin and destination */
349   network->origin.turnMovements = createTurningLinkedList();
350   network->destination.upstreamMovements = createTurningLinkedList();
351   for (i = 0; i < network->numZones; i++) {
352     for (curArc = network->node[i].forwardStar->head; curArc != NULL;
          curArc = curArc->next) {
353       newTurningMovement = newScalar(turning_type);
354       newTurningMovement->upstreamArc = &(network->origin);
355       newTurningMovement->downstreamArc = curArc->arc;
356       newTurningMovement->vehicles = createVehicleDoublyLinkedList();
357       insertTurningLinkedList(network->node[i].turnMovements,
             newTurningMovement, NULL);
358       insertTurningLinkedList(network->origin.turnMovements,
             newTurningMovement, NULL);
359       insertTurningLinkedList(curArc->arc->upstreamMovements,
             newTurningMovement, NULL);
360     }
361     for (curArc = network->node[i].reverseStar->head; curArc != NULL;
          curArc = curArc->next) {
362       newTurningMovement = newScalar(turning_type);
363       newTurningMovement->upstreamArc = curArc->arc;
364       newTurningMovement->downstreamArc = &(network->destination);
365       newTurningMovement->vehicles = createVehicleDoublyLinkedList();
366       insertTurningLinkedList(network->node[i].turnMovements,
             newTurningMovement, NULL);
367       insertTurningLinkedList(curArc->arc->turnMovements,
             newTurningMovement, NULL);
368       insertTurningLinkedList(network->destination.upstreamMovements,
             newTurningMovement, NULL);
369     }
370   }
371
372   while (!feof(nodeControlFile)) {
373     if (fgets(fullLine, STRING_SIZE, nodeControlFile) == NULL) break;
374     status = parseLine(fullLine, trimmedLine);
375     if (status == BLANK_LINE || status == COMMENT) continue;
376     if (strncmp(trimmedLine, "Node", 4) == 0) {
377       sscanf(trimmedLine, "Node %d : %s", &curNode, controlText);
378       if (curNode < 1 || curNode > network->numNodes) {
379             warning(FULL_NOTIFICATIONS, "Node out of range in control
                 file.  Ignoring input line:\n%s\n", fullLine);
380             continue;
381       }
382       curNode--;
383       if        (strcmp(controlText, "FOUR-WAY-STOP") == 0) {
```

```
384         network->node[curNode].control = FOUR_WAY_STOP;
385       } else if (strcmp(controlText, "INTERCHANGE") == 0) {
386         network->node[curNode].control = INTERCHANGE;
387       } else if (strcmp(controlText, "TWO-WAY-STOP") == 0) {
388         network->node[curNode].control = TWO_WAY_STOP;
389         network->node[curNode].controlData = newScalar(twoWayStop_type)
              ;
390         twoWayStopControl = (twoWayStop_type *)(network->node[curNode].
              controlData);
391         twoWayStopControl->minStopPriority = IS_MISSING;
392         twoWayStopControl->priorityList = createPriorityLinkedList();
393       } else if (strcmp(controlText, "BASIC-SIGNAL") == 0) {
394         network->node[curNode].control = BASIC_SIGNAL;
395         network->node[curNode].controlData = newScalar(basicSignal_type
              );
396           basicSignalControl = (basicSignal_type *)(network->node[
                curNode].controlData);
397           basicSignalControl->cycleLength = IS_MISSING;
398           basicSignalControl->greenTime = createLinkedList();
399       } else if (strcmp(controlText, "FANCY-SIGNAL") == 0) {
400         network->node[curNode].control = FANCY_SIGNAL;
401         warning(FULL_NOTIFICATIONS, "Fancy signal control not yet
              implemented!\n");
402       } else if (strcmp(controlText, "CENTROID") == 0) {
403         network->node[curNode].control = CENTROID;
404       } else if (strcmp(controlText, "MERGE") == 0) {
405         network->node[curNode].control = MERGE;
406       } else if (strcmp(controlText, "DIVERGE") == 0) {
407         network->node[curNode].control = DIVERGE;
408       } else if (strcmp(controlText, "NONHOMOGENEOUS") == 0) {
409         network->node[curNode].control = NONHOMOGENEOUS;
410          } else if (strcmp(controlText, "UNKNOWN") == 0) {
411           network->node[curNode].control = UNKNOWN_CONTROL;
412       } else {
413         fatalError("Unknown control type in control file.  Input line
              is:\n%s", fullLine);
414       }
415       if (curNode == IS_MISSING) {
416         warning(LOW_NOTIFICATIONS, "Non-blank, non-comment line found
              before a node has been selected!  Input line is:\n%s\n",
              fullLine);
417         continue;
418       }
419       continue;
420     } else {
421         readTurnMovement(trimmedLine, &(network->node[curNode]));
422     }
```

```
423    }
424    fclose(nodeControlFile);
425
426    displayMessage(FULL_NOTIFICATIONS, "Finished reading node control
          file.\n");
427  }
428
429  /*
430  readParametersFile -- reads the parameters file before starting a run
431  Arguments:
432     thisRun -- pointer to a parameters_type which will have all run
             parameters
433     parametersFileName -- name of node control file
434  */
435  void readParametersFile(struct parameters_type_s *thisRun, char*
        parametersFileName) {
436    int status;
437    char fullLine[STRING_SIZE];
438    char metadataTag[STRING_SIZE], metadataValue[STRING_SIZE];
439    FILE *parametersFile = openFile(parametersFileName, "r");
440
441    /* Initialize (set mandatory values to missing, mandatory strings to
          length zero, others to defaults) */
442    thisRun->networkFileName[0] = '\0';
443    thisRun->demandFileName[0] = '\0';
444    thisRun->coordinateFileName[0] = '\0';
445    thisRun->countsFileName[0] = '\0';
446    thisRun->nodeControlFileName[0] = '\0';
447     thisRun->graphicsFileName[0] = '\0';
448     thisRun->linkSummaryName[0] = '\0';
449     thisRun->nodeSummaryName[0] = '\0';
450    thisRun->timeHorizon = IS_MISSING;
451    thisRun->lastVehicleOn = IS_MISSING;
452    thisRun->warmUpLength = IS_MISSING;
453    thisRun->coolDownLength = IS_MISSING;
454    thisRun->AECtarget = 0;
455    thisRun->maxRunTime = INFINITY;
456    thisRun->maxIterations = INT_MAX;
457    thisRun->demandMultiplier = 1;
458    thisRun->tickLength = IS_MISSING;
459    thisRun->vehicleLength = IS_MISSING;
460    thisRun->backwardWaveRatio = IS_MISSING;
461    thisRun->verbosity = MEDIUM_NOTIFICATIONS;
462    thisRun->demandProfile = UNKNOWN_PROFILE;
463    thisRun->solutionAlgorithm = MSA;
464    thisRun->randomSeed = time(NULL);
465
```

```
466   /* Process parameter file */
467   while (!feof(parametersFile)) {
468     do {
469       if (fgets(fullLine, STRING_SIZE, parametersFile) == NULL) break;
470       status = parseMetadata(fullLine, metadataTag, metadataValue);
471     } while (status == BLANK_LINE || status == COMMENT);
472     if        (strcmp(metadataTag, "NETWORK FILE") == 0) {
473       strcpy(thisRun->networkFileName, metadataValue);
474     } else if (strcmp(metadataTag, "DEMAND FILE") == 0) {
475       strcpy(thisRun->demandFileName, metadataValue);
476     } else if (strcmp(metadataTag, "NODE COORDINATE FILE") == 0) {
477       strcpy(thisRun->coordinateFileName, metadataValue);
478       /* Two values for compatibility with earlier versions */
479     } else if (strcmp(metadataTag, "SUMMARY FILE") == 0 || strcmp(
          metadataTag, "COUNTS FILE") == 0) {
480       strcpy(thisRun->countsFileName, metadataValue);
481     } else if (strcmp(metadataTag, "LINK SUMMARY FILE") == 0) {
482       strcpy(thisRun->linkSummaryName, metadataValue);
483     } else if (strcmp(metadataTag, "NODE SUMMARY FILE") == 0) {
484       strcpy(thisRun->nodeSummaryName, metadataValue);
485     } else if (strcmp(metadataTag, "TIME HORIZON") == 0) {
486       thisRun->timeHorizon = atol(metadataValue);
487     } else if (strcmp(metadataTag, "TICK LENGTH") == 0) {
488       thisRun->tickLength = atof(metadataValue);
489     } else if (strcmp(metadataTag, "LAST VEHICLE ON") == 0) {
490       thisRun->lastVehicleOn = atol(metadataValue);
491     } else if (strcmp(metadataTag, "WARM UP PERIOD") == 0) {
492       thisRun->warmUpLength = atol(metadataValue);
493     } else if (strcmp(metadataTag, "COOL DOWN PERIOD") == 0) {
494       thisRun->coolDownLength = atol(metadataValue);
495     } else if (strcmp(metadataTag, "DELTA") == 0) {
496       warning(LOW_NOTIFICATIONS, "Backward wave ratios now set on a
             link-by-link basis using jam density specified in network file
             .  Ignoring value in parameters file.\n");
497     } else if (strcmp(metadataTag, "AEC TOLERANCE") == 0) {
498       thisRun->AECtarget = atof(metadataValue);
499     } else if (strcmp(metadataTag, "MAX RUN TIME") == 0) {
500       thisRun->maxRunTime = (float) atof(metadataValue);
501     } else if (strcmp(metadataTag, "MAX ITERATIONS") == 0) {
502       thisRun->maxIterations = atoi(metadataValue);
503     } else if (strcmp(metadataTag, "DEMAND MULTIPLIER") == 0) {
504       thisRun->demandMultiplier = (float) atof(metadataValue);
505     } else if (strcmp(metadataTag, "NODE CONTROL FILE") == 0) {
506       strcpy(thisRun->nodeControlFileName, metadataValue);
507     } else if (strcmp(metadataTag, "VERBOSITY LEVEL") == 0) {
508       thisRun->verbosity = (short) atoi(metadataValue);
509     } else if (strcmp(metadataTag, "VEHICLE LENGTH") == 0) {
```

```
510       thisRun->vehicleLength = atof(metadataValue);
511     } else if (strcmp(metadataTag, "BACKWARD WAVE RATIO") == 0) {
512       thisRun->backwardWaveRatio = atof(metadataValue);
513     } else if (strcmp(metadataTag, "GRAPHICS PARAMETERS FILE") == 0) {
514        strcpy(thisRun->graphicsFileName, metadataValue);
515     } else if (strcmp(metadataTag, "RANDOM SEED") == 0) {
516       thisRun->randomSeed = atoi(metadataValue);
517     } else if (strcmp(metadataTag, "DEMAND PROFILE") == 0) {
518       if    (strcmp(metadataValue, "UNIFORM") == 0)   thisRun->
             demandProfile = UNIFORM;
519       else if (strcmp(metadataValue, "PEAK") == 0)    thisRun->
             demandProfile = PEAK;
520       else if (strcmp(metadataValue, "TRIANGLE") == 0) {
521          thisRun->demandProfile = TRIANGLE;
522          thisRun->profileParameters = newScalar(triangleProfile_type);
523           ((triangleProfile_type *)(thisRun->profileParameters))->
                peakTime = IS_MISSING;
524           ((triangleProfile_type *)(thisRun->profileParameters))->
                ratio1 = IS_MISSING;
525           ((triangleProfile_type *)(thisRun->profileParameters))->
                ratio2 = IS_MISSING;
526       }
527       else if (strcmp(metadataValue, "QUADRATIC") == 0) thisRun->
             demandProfile = QUADRATIC;
528       else if (strcmp(metadataValue, "RAW") == 0) thisRun->
             demandProfile = RAW;
529       else    fatalError("Unknown profile type %s\n", metadataValue);
530     } else if (strcmp(metadataTag, "SOLUTION ALGORITHM") == 0) {
531       if    (strcmp(metadataValue, "MSA") == 0)       thisRun->
             solutionAlgorithm = MSA;
532       else if (strcmp(metadataValue, "LUCE") == 0)    thisRun->
             solutionAlgorithm = LUCE;
533       else    fatalError("Unknown algorithm type %s\n", metadataValue);
534     } else if (strcmp(metadataTag, "PEAK DEMAND TIME") == 0) {
535        if (thisRun->demandProfile == TRIANGLE) {
536           ((triangleProfile_type *)(thisRun->profileParameters))->
                peakTime = atoi(metadataValue);
537        } else {
538           warning(LOW_NOTIFICATIONS, "Ignoring PEAK DEMAND TIME
                parameter (must follow definition of the demand profile
                type as TRIANGLE).\n");
539        }
540     } else if (strcmp(metadataTag, "RATIO 1") == 0) {
541        if (thisRun->demandProfile == TRIANGLE) {
542           ((triangleProfile_type *)(thisRun->profileParameters))->
                ratio1 = atof(metadataValue);
543        } else {
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```
544             warning(LOW_NOTIFICATIONS, "Ignoring RATIO 1 parameter (must
                    follow definition of the demand profile type as TRIANGLE)
                    .\n");
545         }
546       } else if (strcmp(metadataTag, "RATIO 2") == 0) {
547          if (thisRun->demandProfile == TRIANGLE) {
548             ((triangleProfile_type *)(thisRun->profileParameters))->
                    ratio2 = atof(metadataValue);
549         } else {
550             warning(LOW_NOTIFICATIONS, "Ignoring RATIO 2 parameter (must
                    follow definition of the demand profile type as TRIANGLE)
                    .\n");
551         }
552       } else {
553          warning(MEDIUM_NOTIFICATIONS, "Ignoring unknown metadata tag in
                    parameters file - %s\n", metadataTag);
554       }
555    }
556
557    /* Check mandatory elements are present and validate input */
558    if (strlen(thisRun->networkFileName) == 0) fatalError("Missing
          network file!");
559    if (strlen(thisRun->demandFileName) == 0) fatalError("Missing demand
          file!");
560    if (strlen(thisRun->coordinateFileName) == 0) fatalError("Missing
          node coordinate file!");
561    if (thisRun->tickLength == IS_MISSING) { thisRun->tickLength = 6;
          warning(LOW_NOTIFICATIONS, "No tick length specified... using 6
          seconds as default.\n"); }
562    if (thisRun->vehicleLength == IS_MISSING) { thisRun->vehicleLength =
          20; warning(LOW_NOTIFICATIONS, "No vehicle length specified...
          using 20 ft as default.\n"); }
563    if (thisRun->backwardWaveRatio == IS_MISSING) { thisRun->
          backwardWaveRatio = 0.5; warning(LOW_NOTIFICATIONS, "No backward
          wave ratio specified... using 0.5 as default.\n"); }
564    if (thisRun->timeHorizon == IS_MISSING) fatalError("Missing time
          horizon!");
565    if (thisRun->lastVehicleOn == IS_MISSING) { thisRun->lastVehicleOn =
          thisRun->timeHorizon * 0.9; warning(FULL_NOTIFICATIONS, "No last
          vehicle on provided... setting to 90%% of time horizon.\n"); }
566    if (thisRun->demandProfile == UNKNOWN_PROFILE) fatalError("Missing or
           unknown demand profile!");
567    if (thisRun->demandMultiplier < 0) fatalError("Negative demand
          multiplier!");
568    if (thisRun->demandMultiplier == 0) warning(LOW_NOTIFICATIONS, "
          Demand multiplier is zero -- no trips will be assigned!\n");
569    if (thisRun->tickLength <= 0) fatalError("Tick length must be
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        positive!");
570     if (thisRun->timeHorizon < thisRun->lastVehicleOn) fatalError("Last
        vehicle enters after time horizon!");
571     if (thisRun->timeHorizon < thisRun->tickLength) fatalError("Tick
        length exceeds time horizon!");
572     if (thisRun->maxIterations == INT_MAX && thisRun->maxRunTime ==
        INFINITY && thisRun->AECtarget == 0) warning(LOW_NOTIFICATIONS, "
        No termination criteria specified... program will run until
        interrupted manually.\n");
573     if (thisRun->demandProfile == TRIANGLE) {
574         if (((triangleProfile_type *)(thisRun->profileParameters))->
            peakTime == IS_MISSING) fatalError("TRIANGLE profile requires
            specification of PEAK DEMAND TIME.");
575         if (((triangleProfile_type *)(thisRun->profileParameters))->
            ratio1 == IS_MISSING) fatalError("TRIANGLE profile requires
            specification of RATIO 1.");
576         if (((triangleProfile_type *)(thisRun->profileParameters))->
            ratio2 == IS_MISSING) fatalError("TRIANGLE profile requires
            specification of RATIO 2.");
577     }
578     if ((strlen(thisRun->linkSummaryName) > 0 || strlen(thisRun->
        nodeSummaryName) > 0)
579             && (thisRun->warmUpLength == IS_MISSING || thisRun->
                coolDownLength == IS_MISSING)) {
580         fatalError("Must provide warm-up and cool-down periods to
            generate summary files.\n");
581     }
582
583     fclose(parametersFile);
584     displayMessage(FULL_NOTIFICATIONS, "Finished reading parameters file
        .\n");
585 }
586
587 void displayRunParameters(int minVerbosity, parameters_type *run) {
588     displayMessage(minVerbosity, "Displaying run parameters:\n\n");
589     displayMessage(minVerbosity, "Network file: %s\n", run->
        networkFileName);
590     displayMessage(minVerbosity, "Demand file: %s\n", run->demandFileName
        );
591     displayMessage(minVerbosity, "Node coordinate file: %s\n", run->
        coordinateFileName);
592     displayMessage(minVerbosity, "Node control file: %s\n", run->
        nodeControlFileName);
593     displayMessage(minVerbosity, "Counts file: %s\n", run->countsFileName
        );
594     displayMessage(minVerbosity, "Node control file: %s\n", run->
        nodeControlFileName);
```

```
595   displayMessage(minVerbosity, "Time horizon: %ld\n", run->timeHorizon)
         ;
596   displayMessage(minVerbosity, "AEC tolerance: %f\n", run->AECtarget);
597   displayMessage(minVerbosity, "Max running time: %f\n", run->
         maxRunTime);
598   displayMessage(minVerbosity, "Vehicle length: %f\n", run->
         vehicleLength);
599 }
600
601 /*
602 writeLinkSummary -- create the link summary file after the DTA run is
       finished (or based on a counts file)
603 Arguments:
604    run -- pointer to a parameters_type which has all run parameters
605    linkSummaryName -- name of file to write link summary data to
606 */
607 void writeLinkSummary(parameters_type *run, char *linkSummaryName) {
608   int ij, t;
609   int last15Volume, peak15Volume, last60Volume, peak60Volume;
610   float time, delay, density, volume, PHF;
611   int startTime = run->warmUpLength / run->tickLength, endTime = (run->
         timeHorizon - run->coolDownLength) / run->tickLength;
612   int numPeriods = endTime - startTime;
613   int length15 = 15 * MINUTES / run->tickLength;
614   int length60 = 60 * MINUTES / run->tickLength;
615   network_type *network = run->network;
616   FILE *summaryFile = openFile(linkSummaryName, "w");
617
618   displayMessage(FULL_NOTIFICATIONS, "Writing link summary file...");
619   if (numPeriods < 1) {
620      warning(LOW_NOTIFICATIONS, "Can't generate link summary file,
            entire run is warm-up or cool-down.\n");
621      return;
622   } else if (numPeriods < length60) {
623       warning(LOW_NOTIFICATIONS, "Insufficient time horizon to
            calculate peak-hour factors.\n");
624   }
625
626   /* Output link cumulative counts */
627   fprintf(summaryFile, "LINK SUMMARY (ALL VALUES TIME AVERAGES)\n");
628   fprintf(summaryFile, "-------------------------------------\n");
629   fprintf(summaryFile, "Link\tTravel time (s)\tDelay (s)\tDensity (veh/
         mi)\tVolume (veh/hr)\tPHF\n");
630   for (ij = 0; ij < network->numArcs; ij++) {
631     fprintf(summaryFile, "(%d,%d)\t", network->arc[ij].tail->ID,
           network->arc[ij].head->ID);
632       /* Calculate link statistics */
```

```
633         time = 0; delay = 0; density = 0; volume = 0; last15Volume = 0;
               last60Volume = 0; peak15Volume = 0; peak60Volume = 0;
634         for (t = startTime; t < endTime; t++) {
635            time += network->arc[ij].travelTime[t];
636            delay += network->arc[ij].travelTime[t] - network->arc[ij].
                  numCells;
637            density += network->arc[ij].upstreamCount[t] - network->arc[ij
                  ].downstreamCount[t];
638            if (t - length15 >= startTime) last15Volume = network->arc[ij
                  ].downstreamCount[t] - network->arc[ij].downstreamCount[t -
                   length15];
639            if (t - length60 >= startTime) last60Volume = network->arc[ij
                  ].downstreamCount[t] - network->arc[ij].downstreamCount[t -
                   length60];
640            peak15Volume = max(last15Volume, peak15Volume);
641            peak60Volume = max(last60Volume, peak60Volume);
642         }
643         volume = network->arc[ij].downstreamCount[endTime] - network->arc
               [ij].downstreamCount[startTime];
644
645         /* Normalize and convert units as necessary */
646         time *= network->tickLength / numPeriods;
647         delay *= network->tickLength / numPeriods;
648         density *= MILES / (network->arc[ij].length * numPeriods);
649         volume *= HOURS / (network->tickLength * numPeriods);
650
651         fprintf(summaryFile, "%.0f\t%.0f\t%.0f\t%.0f\t", time, delay,
               density, volume);
652         if (numPeriods >= length60 && peak15Volume > 0) {
653            PHF = (float) peak60Volume / (4 * peak15Volume);
654            fprintf(summaryFile, "%.2f\n", PHF);
655         } else {
656            fprintf(summaryFile, "---\n");
657         }
658      }
659
660      fclose(summaryFile);
661      displayMessage(FULL_NOTIFICATIONS, "done.\n");
662   }
663
664   /*
665   writeNodeSummary -- create the node summary file after the DTA run is
          finished (or based on a counts file)
666   Arguments:
667      run -- pointer to a parameters_type which has all run parameters
668      nodeSummaryName -- name of file to write node summary data to
669   */
```

```
670 void writeNodeSummary(parameters_type *run, char *nodeSummaryName) {
671   int i, t;
672   int last15Volume, peak15Volume, last60Volume, peak60Volume;
673   float delay, volume, PHF;
674   int startTime = run->warmUpLength / run->tickLength, endTime = (run->
        timeHorizon - run->coolDownLength) / run->tickLength;
675   int numPeriods = endTime - startTime;
676   int length15 = 15 * MINUTES / run->tickLength;
677   int length60 = 60 * MINUTES / run->tickLength;
678   network_type *network = run->network;
679    turningLinkedListElt *curMovement;
680   FILE *summaryFile = openFile(nodeSummaryName, "w");
681
682   displayMessage(FULL_NOTIFICATIONS, "Writing node summary file...");
683   if (numPeriods < 1) {
684      warning(LOW_NOTIFICATIONS, "Can't generate node summary file,
           entire run is warm-up or cool-down.\n");
685      return;
686   } else if (numPeriods < length60) {
687       warning(LOW_NOTIFICATIONS, "Insufficient time horizon to
           calculate peak-hour factors.\n");
688   }
689
690    /* Output movement data */
691    fprintf(summaryFile, "NODE SUMMARY FILE\n");
692    fprintf(summaryFile, "-----------------\n");
693    fprintf(summaryFile, "\tMovement\tDelay (s)\tVolume (vph)\tPHF\n");
694    for (i = 0; i < network->numNodes; i++) {
695       fprintf(summaryFile, "Node %d summary\n", network->node[i].ID);
696       for (curMovement = network->node[i].turnMovements->head;
           curMovement != NULL; curMovement = curMovement->next) {
697          fprintf(summaryFile, "\t%d -> %d -> %d\t", curMovement->
              movement->upstreamArc->tail->ID, network->node[i].ID,
              curMovement->movement->downstreamArc->head->ID);
698          delay = 0; volume = 0; last15Volume = 0; last60Volume = 0;
              peak15Volume = 0; peak60Volume = 0;
699          for (t = startTime; t < endTime; t++) {
700             delay += curMovement->movement->travelTime[t];
701             if (t - length15 >= startTime) last15Volume = curMovement->
                movement->downstreamCount[t] - curMovement->movement->
                downstreamCount[t - length15];
702             if (t - length60 >= startTime) last60Volume = curMovement->
                movement->downstreamCount[t] - curMovement->movement->
                downstreamCount[t - length60];
703             peak15Volume = max(last15Volume, peak15Volume);
704             peak60Volume = max(last60Volume, peak60Volume);
705          }
```

```
706           /* Normalize and convert units as necessary */
707           volume = curMovement->movement->downstreamCount[endTime] -
                 curMovement->movement->downstreamCount[startTime];
708           delay *= network->tickLength / numPeriods;
709           volume *= HOURS / (network->tickLength * numPeriods);
710           PHF = (float) peak60Volume / (4 * peak15Volume);
711           fprintf(summaryFile, "%.0f\t%.0f\t", delay, volume);
712           if (numPeriods >= length60 && peak15Volume > 0) {
713              PHF = (float) peak60Volume / (4 * peak15Volume);
714              fprintf(summaryFile, "%.2f\n", PHF);
715           } else {
716              fprintf(summaryFile, "---\n");
717           }
718        }
719     }
720
721   fclose(summaryFile);
722   displayMessage(FULL_NOTIFICATIONS, "done.\n");
723 }
724
725 /*
726 writeCumulativeCounts -- create the comprehensive counts file after the
        DTA run is finished
727 Arguments:
728    network -- pointer to a network_type which contains all link and
          turn  movement cumulative counts
729    countsFileName -- name of file to write counts data to
730 */
731 void writeCumulativeCounts(network_type *network, char *countsFileName)
       {
732   int i, ij, t;
733   turningLinkedListElt *curMovement;
734   FILE *countsFile = openFile(countsFileName, "w");
735
736   displayMessage(FULL_NOTIFICATIONS, "Writing counts file...");
737
738   /* Output link cumulative counts */
739   fprintf(countsFile, "LINK CUMULATIVE COUNTS\n");
740   fprintf(countsFile, "----------------------\n");
741   fprintf(countsFile, "t");
742   for (ij = 0; ij < network->numArcs; ij++) {
743     fprintf(countsFile, "\t(%d,%d)\tDownstream\tTime", network->arc[ij
          ].tail->ID, network->arc[ij].head->ID);
744   }
745   fprintf(countsFile, "\n");
746   for (t = 0; t < network->timeHorizon; t++) {
747     fprintf(countsFile, "%d", (int) ((t+1) * network->tickLength));
```

```
748       for (ij = 0; ij < network->numArcs; ij++) {
749         fprintf(countsFile, "\t%d\t%d\t%d", network->arc[ij].
              upstreamCount[t], network->arc[ij].downstreamCount[t], (int) (
              network->arc[ij].travelTime[t] * network->tickLength)  );
750       }
751       fprintf(countsFile, "\n");
752     }
753     fprintf(countsFile, "\n");
754
755     /* Turning movement cumulative counts */
756     fprintf(countsFile, "TURN MOVEMENT CUMULATIVE COUNTS\n");
757     fprintf(countsFile, "------------------------------\n");
758     fprintf(countsFile, "t");
759     for (i = network->numZones; i < network->numNodes; i++) {
760       for (curMovement = network->node[i].turnMovements->head;
             curMovement != NULL; curMovement = curMovement->next) {
761         fprintf(countsFile, "\t%d->%d->%d\tDownstream\tTime", curMovement
              ->movement->upstreamArc->tail->ID, i+1, curMovement->movement
              ->downstreamArc->head->ID);
762       }
763     }
764     fprintf(countsFile, "\n");
765     for (t = 0; t < network->timeHorizon; t++) {
766       fprintf(countsFile, "%d", (int) ((t+1) * network->tickLength));
767       for (i = network->numZones; i < network->numNodes; i++) {
768         for (curMovement = network->node[i].turnMovements->head;
                curMovement != NULL; curMovement = curMovement->next) {
769           fprintf(countsFile, "\t%d\t%d\t%d", curMovement->movement->
                upstreamCount[t], curMovement->movement->downstreamCount[t],
                 (int) (curMovement->movement->travelTime[t] * network->
                tickLength));
770         }
771       }
772       fprintf(countsFile, "\n");
773     }
774
775     fclose(countsFile);
776     displayMessage(FULL_NOTIFICATIONS, "done.\n");
777   }
778
779
780   /*
781   readCumulativeCounts -- Reads a cumulative count file, but it must have
        been *written by writeCumulativeCounts*.
782                           Unlike the other file I/O routines, this one is
                                very picky about formatting.
783   Arguments:
```

```
784     network -- pointer to a network_type into which counts will be read
785     countsFileName -- name of file to read counts data from
786  */
787  void readCumulativeCounts(network_type *network, char *countsFileName)
        {
788    int i, ij, t, checkTime;
789    turningLinkedListElt *curMovement;
790    char fullLine[STRING_SIZE];
791    FILE *countsFile = openFile(countsFileName, "r");
792
793    displayMessage(FULL_NOTIFICATIONS, "Reading counts file...");
794
795    /* Input link cumulative counts -- skip first three lines ("LINK
          CUMULATIVE COUNTS", dashes, and header) */
796    fgets(fullLine, STRING_SIZE, countsFile);
797    fgets(fullLine, STRING_SIZE, countsFile);
798    do {
799        fgets(fullLine, STRING_SIZE, countsFile);
800    } while (strstr(fullLine, "\n") == NULL);
801    for (t = 0; t < network->timeHorizon; t++) {
802      fscanf(countsFile, "%d", &checkTime);
803      if (checkTime != (int) ((t+1) * network->tickLength)) fatalError("
           Counts file doesn't match network.");
804      for (ij = 0; ij < network->numArcs; ij++) {
805        if (fscanf(countsFile, "\t%d\t%d\t%d",
806                &(network->arc[ij].upstreamCount[t]),
807                &(network->arc[ij].downstreamCount[t]),
808                &checkTime) != 3) fatalError("Counts file doesn't match
                   network.");
809          network->arc[ij].travelTime[t] /= network->tickLength;
810      }
811      fscanf(countsFile, "\n");
812    }
813    fscanf(countsFile, "\n");
814
815    /* Turning movement cumulative counts -- again skip first three lines
          */
816    fgets(fullLine, STRING_SIZE, countsFile);
817    fgets(fullLine, STRING_SIZE, countsFile);
818    do {
819        fgets(fullLine, STRING_SIZE, countsFile);
820    } while (strstr(fullLine, "\n") == NULL);
821    for (t = 0; t < network->timeHorizon; t++) {
822      fscanf(countsFile, "%d", &checkTime);
823      if (checkTime != (int) ((t+1) * network->tickLength)) fatalError("
           Counts file doesn't match network.");
824      for (i = network->numZones; i < network->numNodes; i++) {
```

```
825         for (curMovement = network->node[i].turnMovements->head;
               curMovement != NULL; curMovement = curMovement->next) {
826            if (fscanf(countsFile, "\t%d\t%d\t%d",
827                  &(curMovement->movement->upstreamCount[t]),
828                  &(curMovement->movement->downstreamCount[t]),
829                  &checkTime) != 3) fatalError("Counts file doesn't
                        match network.");
830            curMovement->movement->travelTime[t] /= network->tickLength
                  ;
831         }
832       }
833       fscanf(countsFile, "\n");
834    }
835    fscanf(countsFile, "\n");
836
837    fclose(countsFile);
838    displayMessage(FULL_NOTIFICATIONS, "done.\n");
839
840 }
841
842 /*
843 writeNodeControlFile -- Outputs current node control information into
       an intersection control file; often used after performing warrant
       analysis.
844 Arguments:
845    network -- pointer to a network_type from which intersection data
          will be read
846    nodeControlFileName -- name of control file to write data to
847 */
848 void writeNodeControlFile(network_type *network,  char *
       nodeControlFileName) {
849    int i;
850
851     FILE *nodeControlFile = openFile(nodeControlFileName, "w");
852
853    for (i = 0; i < network->numNodes; i++) {
854       writeNode(nodeControlFile, network, i); /* Split into separate
             function to allow single-node analysis */
855    }
856
857    fclose(nodeControlFile);
858 }
859
860 /*
861 writeNode -- Writes control data for a specific node, depending on its
       type.
862 Arguments:
```

```
863     nodeControlFileName -- name of control file to write data to
864     network -- pointer to a network_type from which intersection data
           will be read
865     i -- node number to write
866  */
867  void writeNode(FILE *nodeControlFile, network_type *network, int i) {
868     int priority;
869     turningLinkedListElt *curMovement, *priorityMovement;
870     basicSignal_type *signalData;
871     twoWayStop_type *stopData;
872     priorityLinkedListElt *curPriority;
873     linkedListElt *curGreen;
874
875     fprintf(nodeControlFile, "Node %d : ", i+1);
876     switch (network->node[i].control) {
877     case CENTROID:
878        fprintf(nodeControlFile, " CENTROID\n");
879        break;
880     case NONHOMOGENEOUS:
881        fprintf(nodeControlFile, " NONHOMOGENEOUS\n");
882        for (curMovement = network->node[i].turnMovements->head;
              curMovement != NULL; curMovement = curMovement->next) {
883           fprintf(nodeControlFile, "\t%d -> %d -> %d\t%f\n", curMovement
                 ->movement->upstreamArc->tail->ID, i+1, curMovement->
                 movement->downstreamArc->head->ID, curMovement->movement->
                 saturationFlow * HOURS);
884        }
885        break;
886     case MERGE:
887        fprintf(nodeControlFile, " MERGE\n");
888        for (curMovement = network->node[i].turnMovements->head;
              curMovement != NULL; curMovement = curMovement->next) {
889           fprintf(nodeControlFile, "\t%d -> %d -> %d\t%f\n", curMovement
                 ->movement->upstreamArc->tail->ID, i+1, curMovement->
                 movement->downstreamArc->head->ID, curMovement->movement->
                 saturationFlow * HOURS);
890        }
891        break;
892     case DIVERGE:
893        fprintf(nodeControlFile, " DIVERGE\n");
894        for (curMovement = network->node[i].turnMovements->head;
              curMovement != NULL; curMovement = curMovement->next) {
895           fprintf(nodeControlFile, "\t%d -> %d -> %d\t%f\n", curMovement
                 ->movement->upstreamArc->tail->ID, i+1, curMovement->
                 movement->downstreamArc->head->ID, curMovement->movement->
                 saturationFlow * HOURS);
896        }
```

```
897         break;
898      case FOUR_WAY_STOP:
899         fprintf(nodeControlFile, " FOUR-WAY-STOP\n");
900         for (curMovement = network->node[i].turnMovements->head;
               curMovement != NULL; curMovement = curMovement->next) {
901            fprintf(nodeControlFile, "\t%d -> %d -> %d\t%f\n", curMovement
                  ->movement->upstreamArc->tail->ID, i+1, curMovement->
                  movement->downstreamArc->head->ID, curMovement->movement->
                  saturationFlow * HOURS);
902         }
903         break;
904      case BASIC_SIGNAL:
905         fprintf(nodeControlFile, " BASIC-SIGNAL\n");
906         signalData = (basicSignal_type *)(network->node[i].controlData);
907         fprintf(nodeControlFile, "\tCycle length %d\n", signalData->
               cycleLength);
908         for (curMovement = network->node[i].turnMovements->head, curGreen
                = signalData->greenTime->head;
909            curMovement != NULL; curMovement = curMovement->next,
                  curGreen = curGreen->next) {
910            fprintf(nodeControlFile, "\t%d -> %d -> %d\t%d\t%f\n",
                  curMovement->movement->upstreamArc->tail->ID, i+1,
                  curMovement->movement->downstreamArc->head->ID, curGreen->
                  value, curMovement->movement->saturationFlow * HOURS);
911         }
912         break;
913      case TWO_WAY_STOP:
914         fprintf(nodeControlFile, " TWO-WAY-STOP\n");
915         stopData = (twoWayStop_type *)(network->node[i].controlData);
916         fprintf(nodeControlFile, "\tIntersection saturation flow %f\n",
               stopData->saturationFlow * HOURS);
917         fprintf(nodeControlFile, "\tMinimum stop priority %d\n", stopData
               ->minStopPriority);
918         for (curMovement = network->node[i].turnMovements->head;
               curMovement != NULL; curMovement = curMovement->next) {
919            /* Need to search priority lists to find the right one for
                  this node */
920            for (curPriority = stopData->priorityList->head; curPriority
                  != NULL; curPriority = curPriority->next) {
921               priority = curPriority->priorityLevel;
922               for (priorityMovement = curPriority->movements->head;
                     priorityMovement != NULL; priorityMovement =
                     priorityMovement->next) {
923                  if (priorityMovement->movement == curMovement->movement)
                        goto done; /* Found the right movement */
924               }
925            }
```

```
926             /* This line is only reached if no match was found above.  */
927             fatalError("writeNodeControlFile: Movement %d -> %d -> %d is
                   not in any priority list!", curMovement->movement->
                   upstreamArc->tail->ID, i+1, curMovement->movement->
                   downstreamArc->head->ID);
928             /* Otherwise, we jumped to here. */
929             done:
930             fprintf(nodeControlFile, "\t%d -> %d -> %d\t%d\t%f\n",
                   curMovement->movement->upstreamArc->tail->ID, i+1,
                   curMovement->movement->downstreamArc->head->ID, priority,
                   curMovement->movement->saturationFlow * HOURS);
931          }
932          break;
933       case FANCY_SIGNAL:
934          fatalError("Fancy signals not yet implemented!");
935          break;
936       case INTERCHANGE:
937          fprintf(nodeControlFile, " INTERCHANGE\n");
938          for (curMovement = network->node[i].turnMovements->head;
               curMovement != NULL; curMovement = curMovement->next) {
939             fprintf(nodeControlFile, "\t%d -> %d -> %d\t%f\n", curMovement
                   ->movement->upstreamArc->tail->ID, i+1, curMovement->
                   movement->downstreamArc->head->ID, curMovement->movement->
                   saturationFlow * HOURS);
940          }
941          break;
942       case UNKNOWN_CONTROL:
943          fprintf(nodeControlFile, " UNKNOWN\n");
944       }
945
946    }
947
948    /*
949    writeParametersFile -- Writes a parameters file.  Typically used by
          warrant analysis when an "artificial" run must be conducted
950    Arguments:
951       thisRun -- pointer to a parameters_type containing parameters to
             write
952       parametersFileName -- name of the parameters file to create
953    */
954    void writeParametersFile(struct parameters_type_s *thisRun, char*
          parametersFileName) {
955      FILE *parametersFile = openFile(parametersFileName, "w");
956
957       fprintf(parametersFile, "<NETWORK FILE> %s\n", thisRun->
             networkFileName);
958       fprintf(parametersFile, "<DEMAND FILE> %s\n", thisRun->
```

```
         demandFileName);
959      fprintf(parametersFile, "<NODE COORDINATE FILE> %s\n", thisRun->
         coordinateFileName);
960      fprintf(parametersFile, "<COUNTS FILE> %s\n", thisRun->
         countsFileName);
961      fprintf(parametersFile, "<TIME HORIZON> %ld\n", thisRun->timeHorizon
         );
962      fprintf(parametersFile, "<TICK LENGTH> %f\n", thisRun->tickLength);
963      fprintf(parametersFile, "<LAST VEHICLE ON> %ld\n", thisRun->
         lastVehicleOn);
964      fprintf(parametersFile, "<AEC TOLERANCE> %f\n", thisRun->AECtarget);
965      fprintf(parametersFile, "<MAX RUN TIME> %f\n", thisRun->maxRunTime);
966      fprintf(parametersFile, "<MAX ITERATIONS> %d\n", thisRun->
         maxIterations);
967      fprintf(parametersFile, "<DEMAND MULTIPLIER> %f\n", thisRun->
         demandMultiplier);
968      fprintf(parametersFile, "<NODE CONTROL FILE> %s\n", thisRun->
         nodeControlFileName);
969      fprintf(parametersFile, "<VERBOSITY LEVEL> %hd\n", thisRun->
         verbosity);
970      fprintf(parametersFile, "<VEHICLE LENGTH> %f\n", thisRun->
         vehicleLength);
971      fprintf(parametersFile, "<BACKWARD WAVE RATIO> %f\n", thisRun->
         backwardWaveRatio);
972      fprintf(parametersFile, "<RANDOM SEED> %d\n", thisRun->randomSeed);
973      fprintf(parametersFile, "<DEMAND PROFILE> ");
974      switch (thisRun->demandProfile) {
975      case UNIFORM:
976         fprintf(parametersFile, "UNIFORM\n");
977         break;
978      case PEAK:
979         fprintf(parametersFile, "PEAK\n");
980         break;
981      case TRIANGLE:
982         fprintf(parametersFile, "TRIANGLE\n");
983         fprintf(parametersFile, "<PEAK DEMAND TIME> %ld", ((
            triangleProfile_type *)(thisRun->profileParameters))->peakTime
            );
984         fprintf(parametersFile, "<RATIO 1> %f", ((triangleProfile_type *)
            (thisRun->profileParameters))->ratio1);
985         fprintf(parametersFile, "<RATIO 2> %f", ((triangleProfile_type *)
            (thisRun->profileParameters))->ratio2);
986         break;
987      case QUADRATIC:
988         fprintf(parametersFile, "QUADRATIC\n");
989         break;
990      case RAW:
```

```
991         fprintf(parametersFile, "RAW\n");
992         break;
993       default:
994         fatalError("Unknown demand profile type %d when writing
              parameters file!\n", thisRun->demandProfile);
995       }
996       fprintf(parametersFile, "<SOLUTION ALGORITHM> ");
997       switch (thisRun->solutionAlgorithm) {
998       case MSA:
999         fprintf(parametersFile, "MSA\n");
1000        break;
1001      case LUCE:
1002        fprintf(parametersFile, "LUCE\n");
1003        break;
1004      default:
1005        fatalError("Unknown solution algorithm %d when writing parameters
               file!\n", thisRun->solutionAlgorithm);
1006      }
1007
1008    fclose(parametersFile);
1009    displayMessage(FULL_NOTIFICATIONS, "Finished writing parameters file
         .\n");
1010  }
1011
1012  /*********************************************
1013   ** Reading control data for different nodes **
1014   *********************************************/
1015
1016  /*
1017  readTurnMovement -- Reads a line from an intersection control file.
       Because different control types have different data,
1018                     this function just serves as a switch to the right
                           parsing routine.
1019  Arguments:
1020     inputLine -- entire line of the intersection control file to pass to
           appropriate routine
1021     node -- pointer to the node this movement belongs to
1022  */
1023  void readTurnMovement(char *inputLine, node_type *node) {
1024    switch (node->control) {
1025    case CENTROID:
1026      warning(MEDIUM_NOTIFICATIONS, "Centroid %d should not have explicit
             turn movements listed.\n", node->ID);
1027      return;
1028    case NONHOMOGENEOUS:
1029    case DIVERGE:
1030    case MERGE:
```

```
1031    case FOUR_WAY_STOP:
1032    case INTERCHANGE:
1033      readBasicTurnMovement(inputLine, node);
1034      break;
1035    case TWO_WAY_STOP:
1036        readTwoWayStopMovement(inputLine, node);
1037        break;
1038    case BASIC_SIGNAL:
1039        readBasicSignalMovement(inputLine, node);
1040        break;
1041    case FANCY_SIGNAL:
1042      fatalError("Intersection type %d not yet implemented!", node->
            control);
1043    case UNKNOWN_CONTROL:
1044        break;
1045    default:
1046      fatalError("Unknown intersection type %d for node %d", node->
            control, node->ID);
1047    }
1048
1049  }
1050
1051  /*
1052  readBasicTurnMovement -- Reads a turn movement from the "basic"
       intersection types that do not have fancy formatting
1053  Arguments:
1054     inputLine -- entire line of the intersection control file to read
1055     node -- pointer to the node this movement belongs to
1056  */
1057  void readBasicTurnMovement(char *inputLine, node_type *node) {
1058     turning_type *newTurningMovement = newScalar(turning_type);
1059     int numParams;
1060     int h, i, j;
1061     float s;
1062
1063     numParams = sscanf(inputLine, "%d -> %d -> %d %f", &h, &i, &j, &s);
1064     if (numParams != 4) fatalError("Misformatted control sequence.
           Current line is:\n%s", inputLine);
1065     createMovement(newTurningMovement, h, i, j, node);
1066
1067     if (s < 0) fatalError("Turn movement has negative saturation flow!
           Current line is:\n%s", inputLine);
1068     if (s == 0) warning(LOW_NOTIFICATIONS, "Turn movement %d -> %d -> %d
            has zero saturation flow!", h, i, j);
1069     newTurningMovement->saturationFlow = s / HOURS;
1070  }
1071
```

```
1072 /*
1073 readBasicSignalMovement -- Reads a turn movement for a signal (looking
        for cycle length, etc.)
1074 Arguments:
1075    inputLine -- entire line of the intersection control file to read
1076    node -- pointer to the node this movement belongs to
1077 */
1078 void readBasicSignalMovement(char *inputLine, node_type *node) {
1079    turning_type *newTurningMovement = newScalar(turning_type);
1080    basicSignal_type *signalData = (basicSignal_type *)(node->
          controlData);
1081    int numParams;
1082    int h, i, j;
1083    int c, g;
1084    float s;
1085
1086    /* Does this line contain the cycle length? */
1087    if (strstr(inputLine, "Cycle length") != NULL) {
1088       numParams = sscanf(inputLine, "Cycle length %d", &c);
1089       if (numParams != 1) fatalError("Misformatted cycle length control
              sequence in line containing:\n%s", inputLine);
1090       if (c <= 0) fatalError("Basic signal has non-positive cycle
             length!  Current line contains:\n%s", inputLine);
1091       signalData->cycleLength = c;
1092       return;
1093    }
1094
1095    /* If not, it contains a turn movement with green time and
          saturation flow*/
1096    numParams = sscanf(inputLine, "%d -> %d -> %d %d %f", &h, &i, &j, &g
          , &s);
1097    if (numParams != 5) fatalError("Misformatted control sequence in
          line containing:\n%s", inputLine);
1098    createMovement(newTurningMovement, h, i, j, node);
1099
1100    if (s < 0) fatalError("Turn movement has negative saturation flow!
          Current line contains:\n%s", inputLine);
1101    if (s == 0) warning(LOW_NOTIFICATIONS, "Turn movement %d -> %d -> %d
           has zero saturation flow!", h, i, j);
1102    newTurningMovement->saturationFlow = s / HOURS;
1103
1104    if (g <= 0) fatalError("Basic signal turn movement has non-positive
          green time!  Current line contains:\n%s", inputLine);
1105    insertLinkedList(signalData->greenTime, g, NULL); /* This insertion
          has to mirror the insertion in createMovement */
1106 }
1107
```

```
1108 /*
1109 readTwoWayStopMovement -- Reads a turn movement from the two-way stop
        intersection type (looking out for special parameters)
1110 Arguments:
1111    inputLine -- entire line of the intersection control file to read
1112    node -- pointer to the node this movement belongs to
1113 */
1114 void readTwoWayStopMovement(char *inputLine, node_type *node) {
1115    turning_type *newTurningMovement;
1116    priorityLinkedListElt *curPriority, *prevPriority;
1117    twoWayStop_type *stopData = (twoWayStop_type *)(node->controlData);
1118    int numParams;
1119    int h, i, j, p;
1120    float s;
1121
1122    /* Does this line contain an intersection parameter? */
1123    if        (strstr(inputLine, "Minimum stop priority") != NULL) {
1124       numParams = sscanf(inputLine, "Minimum stop priority %d", &
           stopData->minStopPriority);
1125       if (numParams != 1) fatalError("Misformatted minimum stop
           priority control sequence in line containing:\n%s", inputLine)
           ;
1126       return;
1127    } else if (strstr(inputLine, "Intersection saturation flow") != NULL
        ) {
1128       numParams = sscanf(inputLine, "Intersection saturation flow %f",
           &s);
1129       if (numParams != 1) fatalError("Misformatted intersection
           saturation flow control sequence in line containing:\n%s",
           inputLine);
1130       if (s < 0) fatalError("Intersection has negative saturation flow!
             Current line contains:\n%s", inputLine);
1131       if (s == 0) warning(LOW_NOTIFICATIONS, "Intersection %d has zero
           saturation flow!", node->ID);
1132       stopData->saturationFlow = s / HOURS;
1133       return;
1134    }
1135
1136    /* If not, it contains a turn movement with priority level */
1137    newTurningMovement = newScalar(turning_type);
1138    numParams = sscanf(inputLine, "%d -> %d -> %d %d %f", &h, &i, &j, &p
        , &s);
1139    if (numParams != 5) fatalError("Misformatted control sequence in
        line containing:\n%s", inputLine);
1140    createMovement(newTurningMovement, h, i, j, node);
1141    if (s < 0) fatalError("Turn movement has negative saturation flow!
        Current line contains:\n%s", inputLine);
```

```
1142     if (s == 0) warning(LOW_NOTIFICATIONS, "Turn movement %d -> %d -> %d
             has zero saturation flow!", h, i, j);
1143     newTurningMovement->saturationFlow = s / HOURS;
1144
1145     /* Find appropriate place in priority list */
1146     prevPriority = NULL;
1147     for (curPriority = stopData->priorityList->head; curPriority != NULL
            ; curPriority = curPriority->next) {
1148        if (curPriority->priorityLevel >= p) break;
1149        prevPriority = curPriority;
1150     }
1151     if (curPriority == NULL || curPriority->priorityLevel != p) {
1152        curPriority = insertPriorityLinkedList(stopData->priorityList, p,
               prevPriority);
1153     }
1154     insertTurningLinkedList(curPriority->movements, newTurningMovement,
            NULL);
1155 }
1156
1157 /*
1158 createMovement -- Initializes data structures related to a turning_type
        , with some error checking
1159 Arguments:
1160    movement -- pointer to the movement being initialized
1161    upstreamNode -- ID of the upstream intersection for this movement
1162    curNode -- ID of the intersection containing this movement
1163    downstreamNode -- ID of the downstream intersection for this
           movement
1164    node -- pointer to the node this movement belongs to
1165 */
1166 void createMovement(turning_type *movement, int upstreamNode, int
        curNode, int downstreamNode, node_type *node) {
1167     arcLinkedListElt *curArc;
1168
1169     if (curNode != node->ID) fatalError("Turn movement %d -> %d -> %d
            does not match node %d!\n", curNode, node->ID);
1170
1171     /* Find relevant upstream and downstream arcs, insert turning
            movement into relevant data structures */
1172     movement->upstreamArc = NULL;
1173     movement->vehicles = createVehicleDoublyLinkedList();
1174     for (curArc = node->reverseStar->head; curArc != NULL; curArc =
            curArc->next) {
1175        if (curArc->arc->tail->ID == upstreamNode) {
1176           movement->upstreamArc = curArc->arc;
1177           break;
1178        }
```

```
1179     }
1180     if (movement->upstreamArc == NULL) fatalError("Upstream arc not
            found for movement %d -> %d -> %d", upstreamNode, curNode,
            downstreamNode);
1181     movement->downstreamArc = NULL;
1182     for (curArc = node->forwardStar->head; curArc != NULL; curArc =
            curArc->next) {
1183        if (curArc->arc->head->ID == downstreamNode) {
1184           movement->downstreamArc = curArc->arc;
1185           break;
1186        }
1187     }
1188     if (movement->downstreamArc == NULL) fatalError("Downstream arc not
            found for movement %d -> %d -> %d", upstreamNode, curNode,
            downstreamNode);
1189
1190     insertTurningLinkedList(node->turnMovements, movement, NULL);
1191     insertTurningLinkedList(movement->upstreamArc->turnMovements,
            movement, NULL);
1192     insertTurningLinkedList(movement->downstreamArc->upstreamMovements,
            movement, NULL);
1193  }
1194
1195  /***********************
1196   ** String processing **
1197   ***********************/
1198
1199  /*
1200  blankInputString -- Replaces all characters in a string with NULLs
1201  Arguments:
1202     string -- string to blank
1203     length -- string length
1204  */
1205  void blankInputString(char *string, int length) {
1206    int i;
1207    for (i = 0; i < length; i++) string[i] = '\0';
1208  }
1209
1210  /*
1211  parseMetadata -- Splits a metadata line into its metadata tag and value
         .  Metadat tags are marked with <> signs; whitespace between tag and
          value is ignored.
1212  Arguments:
1213     inputLine -- full line from the input file
1214     metadataTag -- string to store the metadata tag
1215     metadataValue -- string to store the metadata value
1216  */
```

```
1217 int parseMetadata(char* inputLine, char* metadataTag, char*
       metadataValue) {
1218   int i = 0, j = 0;
1219   while (inputLine[i] != '<') {
1220     if (inputLine[i] == '\0' || inputLine[i] == '\n' || inputLine[i]
         == '\r') return BLANK_LINE;
1221     if (inputLine[i] == '~') return COMMENT;
1222     i++;
1223   }
1224   i++;
1225   while (inputLine[i] != '\0' && inputLine[i] != '>') {
1226     metadataTag[j++] = toupper(inputLine[i++]);
1227   }
1228   metadataTag[j] = '\0';
1229   if (inputLine[i] == '\0') fatalError("Metadata tag not closed in
       parameters file - ", metadataTag);
1230   i++;
1231   while (inputLine[i] != '\0' && (inputLine[i] == ' ' || inputLine[i]
       == '\t')) i++;
1232   j = 0;
1233   while (inputLine[i] != '\0' && inputLine[i] != '\n' && inputLine[i]
       != '\r' && inputLine[i] != '~') {
1234     metadataValue[j++] = inputLine[i++];
1235   }
1236   metadataValue[j] = '\0';
1237   return SUCCESS;
1238 }
1239
1240 /*
1241 parseLine -- Checks for comments and blank lines, and removes leading
       spaces.  Returns either COMMENT, BLANK_LINE, or SUCCESS based on the
       line
1242 Arguments:
1243    inputLine -- full line from the input file
1244    metadataTag -- string to store the metadata tag
1245    metadataValue -- string to store the metadata value
1246 */
1247 int parseLine(char* inputLine, char* outputLine) {
1248   int i = 0, j = 0;
1249   while (inputLine[i] != '\0' && (inputLine[i] == ' ' || inputLine[i]
       == '\t')) i++;
1250   if (inputLine[i] == '~') return COMMENT;
1251   if (inputLine[i] == '\0' || inputLine[i] == '\n' || inputLine[i] == '
       \r') return BLANK_LINE;
1252   while (inputLine[i] != '\0') {
1253     outputLine[j++] = inputLine[i++];
1254   }
```

```
1255   outputLine[j] = '\0';
1256   return SUCCESS;
1257 }
```

D.1.6 fileio.h

```
 1 #ifndef _FILEIO_H_
 2 #define _FILEIO_H_
 3
 4 #include <ctype.h>
 5 #include <limits.h>
 6 #include <math.h>
 7 #include  <stdio.h>
 8 #include <stdlib.h>
 9 #include <string.h>
10 #include <time.h>
11 #include "dta.h"
12 #include "network.h"
13 #include "sampling.h"
14 #include "utils.h"
15 #include "vehicle.h"
16
17 struct parameters_type_s;
18
19 /* Return codes for metadata parsing */
20 enum {
21   SUCCESS,
22   BLANK_LINE,
23   COMMENT
24 };
25
26 /*********************
27  ** File processing **
28  *********************/
29
30 FILE *openFile(char *filename, char *access);
31
32 void readDemandFile(struct parameters_type_s *run);
33 void readNetworkFile(network_type *network, char *networkFileName,
      float backwardWaveRatio);
34 void readStaticODFile(network_type *network, char *staticODFileName,
      float *demandMultiplier);
35 void readNodeCoordinateFile(network_type *network, char *
      coordinateFileName);
36 void readNodeControlFile(network_type *network, char *
      nodeControlFileName);
37 void readParametersFile(struct parameters_type_s *thisRun, char*
```

```
   parametersFileName);
38 void readRawODTFile(network_type *network, char *rawODTFileName, float
   *demandMultiplier);
39
40 void displayRunParameters(int minVerbosity, struct parameters_type_s *
   run);
41
42 void writeCumulativeCounts(network_type *network, char *countsFileName)
   ;
43 void readCumulativeCounts(network_type *network, char *countsFileName);
44 void writeNodeControlFile(network_type *network,  char *
   nodeControlFileName);
45 void writeNode(FILE *nodeControlFile, network_type *network, int i);
46 void writeParametersFile(struct parameters_type_s *thisRun, char*
   parametersFileName);
47 void writeLinkSummary(struct parameters_type_s *run, char *
   nodeSummaryName);
48 void writeNodeSummary(struct parameters_type_s *run, char *
   nodeSummaryName);
49
50 /*******************************************
51  ** Reading control data for different nodes **
52  *******************************************/
53
54 void readTurnMovement(char *inputLine, node_type *node);
55 void readBasicTurnMovement(char *inputLine, node_type *node);
56 void readBasicSignalMovement(char *inputLine, node_type *node);
57 void readTwoWayStopMovement(char *inputLine, node_type *node);
58 void createMovement(turning_type *movement, int upstreamNode, int
   curNode, int downstreamNode, node_type *node);
59
60 /**********************
61  ** String processing **
62  **********************/
63
64 void blankInputString(char *string, int length);
65 int parseMetadata(char* inputLine, char* metadataTag, char*
   metadataValue);
66 int parseLine(char* inputLine, char* outputLine);
67
68
69 #endif
```

D.1.7 node.c

```
1 #include "node.h"
2
```

```
3  /**** Calculate link parameters ****/
4
5  void calculateReceivingFlows(arc_type *arc) {
6    cellDoublyLinkedListElt *curCell;
7
8    for (curCell = arc->cells->tail; curCell != NULL; curCell = curCell->
        next) {
9      curCell->cell->receivingFlow = min(arc->waveRatio * (arc->
          cellMaxVehicles - curCell->cell->vehicles->size), arc->
          cellCapacity);
10   }
11   arc->receivingFlow = arc->cells->tail->cell->receivingFlow;
12 }
13
14 void calculateSendingFlows(arc_type *arc) {
15   cellDoublyLinkedListElt *curCell;
16
17   for (curCell = arc->cells->tail; curCell != NULL; curCell = curCell->
        next) {
18     curCell->cell->sendingFlow = min(curCell->cell->vehicles->size, arc
          ->cellCapacity);
19   }
20   arc->sendingFlow = arc->cells->head->cell->sendingFlow;
21 }
22
23 /*********************************
24  * PROCESSING SPECIFIC NODE TYPES *
25  *********************************/
26
27 /*
28  These algorithms are used to update the values of capacity and
       targetDelay before calling the generic intersection processor.
29  These node processing algorithms *destroy* the values of sending and
       receiving flows.  They should not be trusted afterwards.
30   */
31
32 void processNode(network_type *network, node_type *node, int t) {
33   switch (node->control) {
34   case CENTROID:
35     processCentroidNode(network, node, t);
36     return; /* Centroid nodes are treated differently than all other
          intersection types */
37   case NONHOMOGENEOUS: /* Capacity and delay values for these
        intersection types are constant */
38   case DIVERGE:        /* Therefore, there is no need to update their
        values each iteration   */
39   case MERGE:        /* (Initialization routines give the correct
```

```
      values for t = 0          */
40    case FOUR_WAY_STOP:
41    case INTERCHANGE:
42      break;
43    case TWO_WAY_STOP:
44        processTwoWayStopNode(node);
45        break;
46    case BASIC_SIGNAL:
47        processBasicSignalNode(network, node);
48        break;
49    case FANCY_SIGNAL:
50      fatalError("Intersection type %d not yet implemented!", node->
          control);
51    case UNKNOWN_CONTROL:
52    default:
53      fatalError("Unknown intersection type %d for node %d", node->
          control, node->ID);
54    }
55    processGeneralIntersection(node, t);
56  }
57
58  /*
59  Processing centroids.
60  Vehicles have already been loaded to origin movements in the main
      simulateCTM loop
61  What remains:
62    Move as many vehicles in origin turn movements to downstream link as
        possible
63    Shift all incoming [sending] flows to the destination turn movement
64    Move all vehicles in destination turn movements to the destination
        node.
65  */
66  void processCentroidNode(network_type *network, node_type *node, int t)
      {
67    turningLinkedListElt *curMovement;
68    vehicle_type *vehicle;
69    turning_type *movement;
70    int movingFlow;
71
72    for (curMovement = node->turnMovements->head; curMovement != NULL;
        curMovement = curMovement->next) {
73      movement = curMovement->movement;
74      if (movement->upstreamArc == &(network->origin)) {
75        /* Move vehicles from origin movement onto downstream links */
76        movingFlow = min(movement->vehicles->size, movement->
            downstreamArc->receivingFlow);
77        while (movingFlow-- > 0) {
```

```
78          vehicle = movement->vehicles->tail->vehicle;
79          transferVehicleToLink(vehicle, movement, movement->
               downstreamArc, t);
80        }
81      } else if (movement->downstreamArc == &(network->destination)) {
82        /* Move vehicles from upstream link onto movement, and then to
             destination */
83        movingFlow = movement->upstreamArc->sendingFlow;
84        while (movingFlow-- > 0) {
85          vehicle = movement->upstreamArc->cells->head->cell->vehicles->
               tail->vehicle;
86          transferVehicleToMovement(vehicle, movement->upstreamArc,
               movement, t);
87          transferVehicleToLink(vehicle, movement, movement->
               downstreamArc, t);
88        }
89      } else { /* Currently, we don't allow centroids to be "through
            nodes" */
90        fatalError("Node %d is a centroid, but turning movement %d -> %d
             -> %d neither loads or removes a vehicle.", node->ID, movement
             ->upstreamArc->tail->ID, node->ID, movement->downstreamArc->
             head->ID);
91      }
92    }
93  }
94
95  /* Get capacities by doing a forward simulation...
96     Set all movement capacities to 0
97     Set all movement sending flows to 0
98     For each upstream link
99        Search through the vehicle DLLE until you have scanned the entire
              sending flow
100       Increase movement sending flow by 1 for each relevant vehicle
101    Go in order of priority list
102       Iterate over turn movements (when through, go back to start)
103          If intersection capacity remains AND movement sending flow
                positive, deduct movement sending flow, increment movement
                capacity
104 Do not change target delay. */
105 void processTwoWayStopNode(node_type *node) {
106    arcLinkedListElt *curArc;
107    turning_type *movement;
108    turningLinkedListElt *curMovement;
109    vehicleDoublyLinkedListElt *curVehicle;
110    priorityLinkedListElt *curPriority;
111    twoWayStop_type *stopData = (twoWayStop_type *) node->controlData;
112    int veh, remainingCapacity;
```

```
113     bool finishedPriority;
114
115     /* Step 1. Initialize */
116     for (curMovement = node->turnMovements->head; curMovement != NULL;
           curMovement = curMovement->next) {
117        curMovement->movement->capacity = 0;
118        curMovement->movement->sendingFlow = curMovement->movement->
              vehicles->size;
119     }
120
121     /* Step 2. Classify sending flows by movement */
122     for (curArc = node->reverseStar->head; curArc != NULL; curArc =
           curArc->next) {
123        for (curVehicle = curArc->arc->cells->head->cell->vehicles->tail,
              veh = 0;
124              curVehicle != NULL && veh < curArc->arc->sendingFlow;
125              curVehicle = curVehicle->prev, veh++) {
126           movement = curVehicle->vehicle->curPathPosition->movement;
127           movement->sendingFlow++;
128           displayMessage(FULL_DEBUG, "Found vehicle %d of %d for %d -> %
                 d -> %d\n", veh+1, curArc->arc->sendingFlow, movement->
                 upstreamArc->tail->ID, movement->upstreamArc->head->ID,
                 movement->downstreamArc->head->ID);
129        }
130     }
131
132     /* Step 3. Go in order of priority list, allocating capacity as
           possible */
133     remainingCapacity = stopData->capacity;
134     for (curPriority = stopData->priorityList->head; curPriority != NULL
           ; curPriority = curPriority->next) {
135        finishedPriority = FALSE;
136        while (finishedPriority == FALSE) {
137          displayMessage(FULL_DEBUG, "Processing priority level %d;
                 remaining capacity is %d\n", curPriority->priorityLevel,
                 remainingCapacity);
138           finishedPriority = TRUE;
139           for (curMovement = curPriority->movements->head; curMovement
                 != NULL; curMovement = curMovement->next) {
140            displayMessage(FULL_DEBUG, "Considering movement %d -> %d ->
                    %d with sending flow %d\n", curMovement->movement->
                    upstreamArc->tail->ID, curMovement->movement->upstreamArc
                    ->head->ID, curMovement->movement->downstreamArc->head->ID
                    , curMovement->movement->sendingFlow);
141              if (curMovement->movement->sendingFlow == 0) continue;
142              if (remainingCapacity == 0) return; /* No more capacity
                    left, so we are done */
```

```
143             curMovement->movement->sendingFlow--;
144             curMovement->movement->capacity++;
145             remainingCapacity--;
146             displayMessage(FULL_DEBUG, "Increment capacity for %d -> %d
                    -> %d\n", curMovement->movement->upstreamArc->tail->ID,
                    curMovement->movement->upstreamArc->head->ID,
                   curMovement->movement->downstreamArc->head->ID);
147             finishedPriority = FALSE;
148          }
149       }
150    }
151 }
152
153 /* Get v/c by comparing vehicles in the turning movement to capacity [
       will lag by one, but shouldn't matter too much] and delay.  Do not
       change capacities */
154 void processBasicSignalNode(network_type *network, node_type *node) {
155    turningLinkedListElt *curMovement;
156    linkedListElt *curGreenTime;
157    basicSignal_type *signalData = (basicSignal_type *) node->
          controlData;
158    float degreeOfSaturation;
159    float greenFraction;
160
161    for (curMovement = node->turnMovements->head, curGreenTime =
          signalData->greenTime->head;
162         curMovement != NULL && curGreenTime != NULL;
163         curMovement = curMovement->next, curGreenTime = curGreenTime->
             next) {
164       degreeOfSaturation = ((float) curMovement->movement->vehicles->
             size) / curMovement->movement->capacity;
165       greenFraction = ((float) curGreenTime->value) / signalData->
             cycleLength;
166       curMovement->movement->targetDelay = 0.5 * signalData->
             cycleLength * (1 - greenFraction) / (1 - min(1,
             degreeOfSaturation) * greenFraction);
167       curMovement->movement->targetDelay /= network->tickLength;
168     displayMessage(FULL_DEBUG, "Set movement %d -> %d -> %d target to
          delay %d based on degree of saturation %f and green fraction %f\
          n", curMovement->movement->upstreamArc->tail->ID, node->ID,
          curMovement->movement->downstreamArc->head->ID, curMovement->
          movement->targetDelay, degreeOfSaturation, greenFraction);
169    }
170 }
171
172 /*******************************
173  * CORE INTERSECTION PROCESSING *
```

```
174   ******************************/
175
176 void processGeneralIntersection(node_type *node, int t) {
177   turningLinkedListElt *curMovement;
178   arcLinkedListElt *downstreamArc;
179   int pastTime;
180
181   if (verbosity >= FULL_DEBUG) {
182     displayMessage(FULL_DEBUG, "Processing node %d at time %d\n", node
          ->ID, t);
183     displayMessage(FULL_DEBUG, "Sending flows:\n", node->ID, t);
184     for (downstreamArc = node->reverseStar->head; downstreamArc != NULL
          ; downstreamArc = downstreamArc->next) {
185       displayMessage(FULL_DEBUG, "(%d,%d)\t%d\n", downstreamArc->arc->
            tail->ID, node->ID, downstreamArc->arc->sendingFlow);
186     }
187     displayMessage(FULL_DEBUG, "Receiving flows:\n", node->ID, t);
188     for (downstreamArc = node->forwardStar->head; downstreamArc != NULL
          ; downstreamArc = downstreamArc->next) {
189       displayMessage(FULL_DEBUG, "(%d,%d)\t%d\n", node->ID,
            downstreamArc->arc->head->ID, downstreamArc->arc->
            receivingFlow);
190     }
191
192   }
193
194   /* Phase I. Move vehicles from upstream links into turn movements */
195   moveVehiclesIntoIntersectionMovements(node, t);
196
197   /* Phase II. Recalculate necessary values and turn movement sending
        flows */
198   for (downstreamArc = node->forwardStar->head; downstreamArc != NULL;
        downstreamArc = downstreamArc->next) {
199     downstreamArc->arc->receivingFlow = downstreamArc->arc->cells->tail
          ->cell->receivingFlow;
200   }
201   for (curMovement = node->turnMovements->head; curMovement != NULL;
        curMovement = curMovement->next) {
202     pastTime = t - curMovement->movement->targetDelay;
203     pastTime = max(pastTime, 0);
204     curMovement->movement->sendingFlow = curMovement->movement->
          upstreamCount[pastTime] - curMovement->movement->downstreamCount
          [t];
205   }
206
207   /* Phase III. Move vehicles from turn movements onto downstream links
        */
```

```
208   for (downstreamArc = node->forwardStar->head; downstreamArc != NULL;
         downstreamArc = downstreamArc->next) {
209     processMergeFlows(downstreamArc->arc->upstreamMovements, t);
210   }
211 }
212
213
214 void moveVehiclesIntoIntersectionMovements(node_type *node, int t) {
215   turningLinkedListElt *curMovement;
216   vehicleDoublyLinkedListElt *curVehicle;
217   arcLinkedListElt *upstreamArc, *downstreamArc;
218   cell_type *upstreamCell;
219   turning_type *movement;
220   int veh;
221
222   /* 1. Initialize and calculate movement sending flows from arc
         sending flows */
223   for (curMovement = node->turnMovements->head; curMovement != NULL;
         curMovement = curMovement->next) {
224     curMovement->movement->flow = 0;
225     curMovement->movement->sendingFlow = curMovement->movement->
         vehicles->size;
226   }
227   for (upstreamArc = node->reverseStar->head; upstreamArc != NULL;
         upstreamArc = upstreamArc->next) {
228     upstreamCell = upstreamArc->arc->cells->head->cell;
229     for (veh = 0, curVehicle = upstreamCell->vehicles->tail; curVehicle
          != NULL && veh < upstreamArc->arc->sendingFlow; veh++,
         curVehicle = curVehicle->prev) {
230       movement = curVehicle->vehicle->curPathPosition->movement;
231       movement->sendingFlow++;
232     }
233   }
234   displayMessage(FULL_DEBUG, "Movement sending flows and capacities [
         size]:\n");
235   for (curMovement = node->turnMovements->head; curMovement != NULL;
         curMovement = curMovement->next) {
236     curMovement->movement->sendingFlow = min(curMovement->movement->
         sendingFlow, curMovement->movement->capacity);
237     displayMessage(FULL_DEBUG, "%d -> %d -> %d\t%d\t%d\t[%d]\n",
         curMovement->movement->upstreamArc->tail->ID, node->ID,
         curMovement->movement->downstreamArc->head->ID, curMovement->
         movement->sendingFlow, curMovement->movement->capacity,
         curMovement->movement->vehicles->size);
238   }
239
240   /* 2. Calculate each turning movement's receiving flow */
```

```
241    for (downstreamArc = node->forwardStar->head; downstreamArc != NULL;
          downstreamArc = downstreamArc->next) {
242      calculateMergeFlows(downstreamArc->arc->upstreamMovements);
243    }
244    for (curMovement = node->turnMovements->head; curMovement != NULL;
          curMovement = curMovement->next) {
245      curMovement->movement->receivingFlow = curMovement->movement->flow;
246    }
247
248    if (verbosity >= FULL_DEBUG) {
249      displayMessage(FULL_DEBUG, "Calculated movement receiving flows:\n"
           );
250      for (curMovement = node->turnMovements->head; curMovement != NULL;
            curMovement = curMovement->next) {
251        displayMessage(FULL_DEBUG, "%d -> %d -> %d\t%d\n", curMovement->
             movement->upstreamArc->tail->ID, node->ID, curMovement->
             movement->downstreamArc->head->ID, curMovement->movement->
             receivingFlow);
252      }
253    }
254
255
256
257    /* 3. Load vehicles onto movements */
258    for (upstreamArc = node->reverseStar->head; upstreamArc != NULL;
          upstreamArc = upstreamArc->next) {
259      processDivergeFlows(upstreamArc->arc->turnMovements, t);
260    }
261  }
262
263  /* Moves vehicles from an upstream link onto turning movements in a
       diverge-like fashion */
264  int processDivergeFlows(turningLinkedList *divergeMovements, int t) {
265     arc_type *upstreamArc = divergeMovements->head->movement->
          upstreamArc;
266     cell_type *upstreamCell = upstreamArc->cells->head->cell;
267     vehicle_type *vehicle;
268     turning_type *movement;
269     int movingFlow = upstreamArc->sendingFlow;
270     int vehiclesMoved = 0;
271
272     while (movingFlow-- > 0) {
273        vehicle = upstreamCell->vehicles->tail->vehicle;
274        movement = vehicle->curPathPosition->movement;
275        if (movement->receivingFlow > 0) { /* Load vehicle onto movement
              */
276           transferVehicleToMovement(vehicle, movement->upstreamArc,
```

```
                movement, t);
277             vehiclesMoved++;
278             upstreamArc->sendingFlow--;
279             movement->receivingFlow--;
280             displayMessage(FULL_DEBUG, "Moved vehicle onto movement %d ->
                   %d -> %d\n", movement->upstreamArc->tail->ID, movement->
                   upstreamArc->head->ID, movement->downstreamArc->head->ID);
281          } else { /* Downstream receiving flow limits vehicle transfer;
                cut off all other flow*/
282             break;
283          }
284       }
285
286       return vehiclesMoved;
287    }
288
289    /* Moves vehicles from turning movements onto a downstream link in a
          merge-like fashion */
290    int processMergeFlows(turningLinkedList *mergeMovements, int t) {
291      int ij, vehiclesMoved = 0;
292      arc_type *downstreamArc = mergeMovements->head->movement->
            downstreamArc;
293      turningLinkedListElt *curMovement;
294      vehicle_type *vehicle;
295
296      calculateMergeFlows(mergeMovements);
297      for (ij = 0, curMovement = mergeMovements->head; curMovement != NULL;
             ij++, curMovement = curMovement->next) {
298        while (curMovement->movement->flow-- > 0) {
299          vehicle = curMovement->movement->vehicles->tail->vehicle;
300             transferVehicleToLink(vehicle, curMovement->movement,
                   downstreamArc, t);
301             vehiclesMoved++;
302             displayMessage(FULL_DEBUG, "Moved vehicle from movement %d ->
                   %d -> %d\n", curMovement->movement->upstreamArc->tail->ID,
                   curMovement->movement->upstreamArc->head->ID, curMovement->
                   movement->downstreamArc->head->ID);
303        }
304      }
305      return vehiclesMoved;
306    }
307
308    void calculateMergeFlows(turningLinkedList *mergeMovements) {
309      int ij, totalCapacity;
310      float remainingFlow;
311      arc_type *downstreamArc = mergeMovements->head->movement->
            downstreamArc;
```

```
312   turningLinkedListElt *curMovement;
313   declareMatrix(float, mergeFlows, mergeMovements->size, 1);
314
315   for (ij = 0, curMovement = mergeMovements->head; curMovement != NULL;
          ij++, curMovement = curMovement->next) {
316     mergeFlows[ij][0] = 0;
317   }
318
319   do {
320     totalCapacity = 0;
321     remainingFlow = downstreamArc->receivingFlow;
322     for (ij = 0, curMovement = mergeMovements->head; curMovement !=
            NULL; ij++, curMovement = curMovement->next) {
323       if (curMovement->movement->sendingFlow > mergeFlows[ij][0])
            totalCapacity += curMovement->movement->capacity;
324       remainingFlow -= mergeFlows[ij][0];
325     }
326     if (totalCapacity == 0 || remainingFlow < MOVING_FLOW_EPSILON)
          break; /* No additional vehicles can move */
327     for (ij = 0, curMovement = mergeMovements->head; curMovement !=
            NULL; ij++, curMovement = curMovement->next) {
328       mergeFlows[ij][0] = min(curMovement->movement->sendingFlow,
            mergeFlows[ij][0] + remainingFlow * curMovement->movement->
            capacity / totalCapacity);
329     }
330   } while (remainingFlow > 0); /* Loop while receiving flow remains */
331
332   if (verbosity >= FULL_DEBUG) {
333     displayMessage(FULL_DEBUG, "Unrounded merge flows:\n");
334     for (ij = 0, curMovement = mergeMovements->head; curMovement !=
            NULL; ij++, curMovement = curMovement->next) {
335       displayMessage(FULL_DEBUG, "%d -> %d -> %d\t%f\n", curMovement->
            movement->upstreamArc->tail->ID, curMovement->movement->
            upstreamArc->head->ID, curMovement->movement->downstreamArc->
            head->ID, mergeFlows[ij][0]);
336     }
337   }
338
339   roundStochasticMatrix(mergeFlows, mergeMovements->size, 1,
         MERGE_PRECISION);
340
341   displayMessage(FULL_DEBUG, "Rounded merge flows:\n");
342   for (ij = 0, curMovement = mergeMovements->head; curMovement != NULL;
          ij++, curMovement = curMovement->next) {
343     curMovement->movement->flow = mergeFlows[ij][0];
344     displayMessage(FULL_DEBUG, "%d -> %d -> %d\t%d\n", curMovement->
            movement->upstreamArc->tail->ID, curMovement->movement->
```

```
          upstreamArc->head->ID, curMovement->movement->downstreamArc->
          head->ID, curMovement->movement->flow);
345     }
346
347     deleteMatrix(mergeFlows, mergeMovements->size);
348   }
349
350   /**********************
351    * NODE INITIALIZATION *
352    **********************/
353
354   void initializeNodes(network_type *network) {
355     int i;
356     for (i = 0; i < network->numNodes; i++) {
357       switch (network->node[i].control) {
358       case CENTROID:
359         continue; /* No need to initialize centroids */
360       case NONHOMOGENEOUS:
361         initializeNonhomogeneousNode(network, &network->node[i]);
362         break;
363       case DIVERGE:
364         initializeDivergeNode(network, &network->node[i]);
365         break;
366       case MERGE:
367         initializeMergeNode(network, &network->node[i]);
368         break;
369       case FOUR_WAY_STOP:
370         initializeFourWayStopNode(network, &network->node[i]);
371         break;
372       case TWO_WAY_STOP:
373           initializeTwoWayStopNode(network, &network->node[i]);
374           break;
375       case BASIC_SIGNAL:
376           initializeBasicSignalNode(network, &network->node[i]);
377           break;
378       case INTERCHANGE:
379           initializeInterchangeNode(network, &network->node[i]);
380           break;
381       case FANCY_SIGNAL:
382         fatalError("Intersection type %d not yet implemented!", network->
              node[i].control);
383       case UNKNOWN_CONTROL:
384       default:
385         fatalError("Unknown intersection type %d for node %d", network->
              node[i].control, network->node[i].ID);
386       }
387     }
```

```
388 }
389
390 void initializeNonhomogeneousNode(network_type *network, node_type *
       node) {
391   turningLinkedListElt *curMovement;
392   for (curMovement = node->turnMovements->head; curMovement != NULL;
          curMovement = curMovement->next) {
393     curMovement->movement->capacity = ceil(curMovement->movement->
          saturationFlow * network->tickLength);
394     curMovement->movement->targetDelay = 0;
395   }
396 }
397
398 void initializeDivergeNode(network_type *network, node_type *node) {
399   turningLinkedListElt *curMovement;
400   for (curMovement = node->turnMovements->head; curMovement != NULL;
          curMovement = curMovement->next) {
401     curMovement->movement->capacity = ceil(curMovement->movement->
          saturationFlow * network->tickLength);
402     curMovement->movement->targetDelay = 0;
403   }
404 }
405
406 void initializeMergeNode(network_type *network, node_type *node) {
407   turningLinkedListElt *curMovement;
408   for (curMovement = node->turnMovements->head; curMovement != NULL;
          curMovement = curMovement->next) {
409     curMovement->movement->capacity = ceil(curMovement->movement->
          saturationFlow * network->tickLength);
410     curMovement->movement->targetDelay = 0;
411   }
412 }
413
414 void initializeTwoWayStopNode(network_type *network, node_type *node) {
415    turningLinkedListElt *curMovement;
416    priorityLinkedListElt *curPriority;
417    twoWayStop_type *stopData = (twoWayStop_type *)(node->controlData);
418    stopData->capacity = ceil(stopData->saturationFlow * network->
          tickLength);
419    for (curPriority = stopData->priorityList->head; curPriority != NULL
          ; curPriority = curPriority->next) {
420       for (curMovement = curPriority->movements->head; curMovement !=
             NULL; curMovement = curMovement->next) {
421          curMovement->movement->targetDelay = (curPriority->
             priorityLevel < stopData->minStopPriority) ? 0 : ceil(
             STOP_DELAY / network->tickLength);
422          curMovement->movement->capacity = ceil(curMovement->movement->
```

```
                saturationFlow * network->tickLength);
423         }
424       }
425   }
426
427   void initializeFourWayStopNode(network_type *network, node_type *node)
         {
428     turningLinkedListElt *curMovement;
429     for (curMovement = node->turnMovements->head; curMovement != NULL;
           curMovement = curMovement->next) {
430       curMovement->movement->capacity = ceil(curMovement->movement->
           saturationFlow * network->tickLength);
431       curMovement->movement->targetDelay = ceil(STOP_DELAY / network->
           tickLength);
432     }
433   }
434
435   void initializeBasicSignalNode(network_type *network, node_type *node)
         {
436     turningLinkedListElt *curMovement;
437     for (curMovement = node->turnMovements->head; curMovement != NULL;
           curMovement = curMovement->next) {
438       curMovement->movement->capacity = ceil(curMovement->movement->
           saturationFlow * network->tickLength);
439     }
440   }
441
442   void initializeInterchangeNode(network_type *network, node_type *node)
         {
443     turningLinkedListElt *curMovement;
444     for (curMovement = node->turnMovements->head; curMovement != NULL;
           curMovement = curMovement->next) {
445       curMovement->movement->capacity = ceil(curMovement->movement->
           saturationFlow * network->tickLength);
446       curMovement->movement->targetDelay = 0;
447     }
448   }
449
450   /**** Intersection data structures ****/
451
452   priorityLinkedList *createPriorityLinkedList() {
453     declareScalar(priorityLinkedList, newll);
454     newll->head = NULL;
455     newll->tail = NULL;
456     newll->size = 0;
457     return newll;
458   }
```

```
459
460 priorityLinkedListElt *insertPriorityLinkedList(priorityLinkedList *
       list, int priorityLevel, priorityLinkedListElt *after) {
461   declareScalar(priorityLinkedListElt, newNode);
462   newNode->priorityLevel = priorityLevel;
463   newNode->movements = createTurningLinkedList();
464   if (after != NULL) { /* Not inserting at head */
465     newNode->next = after->next;
466     if (list->tail == after) list->tail = newNode;
467     after->next = newNode;
468   } else { /* Inserting at head */
469     newNode->next = list->head;
470     if (list->tail == after) list->tail = newNode;
471     list->head = newNode;
472   }
473   list->size++;
474   return newNode;
475 }
476
477 void deletePriorityLinkedList(priorityLinkedList *list) {
478   priorityLinkedListElt *savenode, *curnode = list->head;
479   while (curnode != NULL) {
480     savenode = curnode->next;
481     deleteTurningLinkedList(curnode->movements);
482     killScalar(curnode);
483     curnode = savenode;
484   }
485   killScalar(list);
486 }
```

D.1.8 node.h

```
1  #ifndef _NODE_H_
2  #define _NODE_H_
3
4  #include <limits.h>
5  #include "network.h"
6  #include "sampling.h"
7  #include "vehicle.h"
8
9  /* Consider a "merge" calculation converged if 99% of flow has been
      assigned (should be enough given rounding) */
10 #define MOVING_FLOW_EPSILON 0.01
11 /* Bits of precision to use for stochastic rounding.  Experiment to
      find good default value */
12 #define MERGE_PRECISION 3
13 /* Minimum floating-point receiving flow to allow a vehicle to enter a
```

```
   link */
#define MIN_INTERSECTION_RECEIVING_FLOW 0.99

/* Seconds of delay at a stop sign (in the absence of conflicting flows
   ) */
#define STOP_DELAY 4

/**** Intersection-specific structs ****/

typedef struct basicSignal_type_s {
   int cycleLength;
   linkedList *greenTime; /* Contains each phase's green time in the
      same order as the node's turningLinkedList */
} basicSignal_type;

typedef struct twoWayStop_type_s {
   int minStopPriority; /* Lowest priority set of movements which must
      stop at the sign */
   float saturationFlow; /* Maximum saturation flow *for the entire
      intersection* in natural units */
   int capacity; /* Maximum vehicles that can flow through intersection
       in a simulation tick */
   struct priorityLinkedList_s *priorityList; /* Linked list for the
      number of priority levels, itself linking to a list of movements
      for that priority level */
} twoWayStop_type;



/**** Calculate link parameters ****/

void calculateReceivingFlows(arc_type *arc);
void calculateSendingFlows(arc_type *arc);

/**** Processing specific node types ****/

void processNode(network_type *network, node_type *node, int t);
void processCentroidNode(network_type *network, node_type *node, int t)
   ;
void processTwoWayStopNode(node_type *node);
void processBasicSignalNode(network_type *network, node_type *node);

/**** Core intersection processing ****/

void processGeneralIntersection(node_type *node, int t);
void moveVehiclesIntoIntersectionMovements(node_type *node, int t);
int processDivergeFlows(turningLinkedList *divergeMovements, int t);
```

```
52 int processMergeFlows(turningLinkedList *mergeMovements, int t);
53 void calculateMergeFlows(turningLinkedList *mergeMovements);
54
55 /**** Node initialization ****/
56
57 void initializeNodes(network_type *network);
58 void initializeNonhomogeneousNode(network_type *network, node_type *
      node);
59 void initializeDivergeNode(network_type *network, node_type *node);
60 void initializeMergeNode(network_type *network, node_type *node);
61 void initializeTwoWayStopNode(network_type *network, node_type *node);
62 void initializeFourWayStopNode(network_type *network, node_type *node);
63 void initializeBasicSignalNode(network_type *network, node_type *node);
64 void initializeInterchangeNode(network_type *network, node_type *node);
65
66 /**** Intersection data structures ****/
67
68 typedef struct priorityLinkedListElt_s {
69   int priorityLevel;
70   struct turningLinkedList_s *movements;
71   struct priorityLinkedListElt_s *next;
72 } priorityLinkedListElt;
73
74 typedef struct priorityLinkedList_s {
75   priorityLinkedListElt *head;
76   priorityLinkedListElt *tail;
77   long size;
78 } priorityLinkedList;
79
80 priorityLinkedList *createPriorityLinkedList();
81 priorityLinkedListElt *insertPriorityLinkedList(priorityLinkedList *
      list, int priorityLevel, priorityLinkedListElt *after);
82 void deletePriorityLinkedList(priorityLinkedList *list);
83
84 #endif
```

D.1.9 vehicle.c

```
1 #include "vehicle.h"
2
3 /**** Link motion ****/
4
5 void moveIntralinkVehicles(arc_type *arc) {
6   int movingFlow;
7   cellDoublyLinkedListElt *curCell;
8
9   /* If there are [1, 2, ..., n] cells, shift 1->2, 2->3, ..., (n-1)->n
```

```
      */
10   for (curCell = arc->cells->tail; curCell != NULL; curCell = curCell->
        next) {
11     if (curCell->next == NULL) break; /* Avoid OB1 error */
12     movingFlow = min(curCell->cell->sendingFlow, curCell->next->cell->
         receivingFlow);
13     while (movingFlow-- > 0) advanceVehicle(curCell);
14   }
15 }
16
17
18 /* Advances a vehicle to adjacent cell *within a link*. */
19 void advanceVehicle(cellDoublyLinkedListElt *curCell) {
20   vehicle_type *vehicle = curCell->cell->vehicles->tail->vehicle;
21   deleteVehicleDoublyLinkedListElt(vehicle->list, vehicle->listElt);
22   vehicle->list = curCell->next->cell->vehicles;
23   vehicle->listElt = insertVehicleDoublyLinkedList(vehicle->list,
        vehicle, NULL);
24 }
25
26 /*
27 Note that these transfer codes require that a vehicle's movement be
     LINK - MOVEMENT - LINK - MOVEMENT - LINK, etc.
28 Artificial origin and destination links help with this
29 Shifts vehicle from its current turn movement to the *upstream* end of
     a link
30 */
31 void transferVehicleToLink(vehicle_type *vehicle, turning_type *
     fromMovement, arc_type *toArc, int t) {
32   fromMovement->downstreamCount[t]++;
33   deleteVehicleDoublyLinkedListElt(vehicle->list, vehicle->listElt);
34   vehicle->list = toArc->cells->tail->cell->vehicles;
35   vehicle->listElt = insertVehicleDoublyLinkedList(vehicle->list,
        vehicle, NULL);
36   toArc->upstreamCount[t]++;
37   vehicle->curPathPosition = vehicle->curPathPosition->next;
38 }
39
40 /* Shifts vehicle from its current link to the *upstream* end of a
     turning movement */
41 void transferVehicleToMovement(vehicle_type *vehicle, arc_type *fromArc
     , turning_type *toMovement, int t) {
42   fromArc->downstreamCount[t]++;
43   deleteVehicleDoublyLinkedListElt(vehicle->list, vehicle->listElt);
44   vehicle->list = toMovement->vehicles;
45   vehicle->listElt = insertVehicleDoublyLinkedList(vehicle->list,
        vehicle, NULL);
```

```
46    toMovement->upstreamCount[t]++;
47  }
48
49
50  float averageExcessCost(network_type *network) {
51    displayMessage(DEBUG, "Calculating AEC based on TSTT %ld and SPTT %ld
          (# vehicles %ld)\n", totalSystemTravelTime(network),
        shortestPathTravelTime(network), network->numVehicles);
52    return (totalSystemTravelTime(network) - shortestPathTravelTime(
        network)) / (float) network->numVehicles;
53  }
54
55  /*
56  Calculates total travel time if everyone were to be loaded on shortest
       paths
57  *Assumes that travel times have not changed since last call to TDSP, i.
       e. that the shortest path is included in the network pathset
58  */
59  long shortestPathTravelTime(network_type *network) {
60    long SPTT = 0;
61    pathLinkedListElt *curPath;
62    int ODTminCost;
63    long odt;
64
65    for (odt = 0; odt < network->numODTs; odt++) {
66      ODTminCost = network->timeHorizon + 1;
67      for (curPath = network->ODT[odt].paths->head; curPath != NULL;
           curPath = curPath->next) {
68        ODTminCost = min(ODTminCost, curPath->path->travelTime);
69      }
70      SPTT += ODTminCost * network->ODT[odt].demand;
71    }
72
73    return SPTT * network->tickLength;
74  }
75
76  /* Calculates total travel time using actual paths. */
77  long totalSystemTravelTime(network_type *network) {
78    long odt, TSTT = 0;
79    vehicleDoublyLinkedListElt *curVehicle;
80
81    for (odt = 0; odt < network->numODTs; odt++) {
82      for (curVehicle = network->ODT[odt].vehicles->head; curVehicle !=
           NULL; curVehicle = curVehicle->next) {
83        TSTT += curVehicle->vehicle->path->travelTime;
84      }
85    }
```

```
86
87    return TSTT * network->tickLength;
88  }
89
90  int latestArrivalTime(network_type *network) {
91    long t, odt, latestArrival = 0;
92    vehicleDoublyLinkedListElt *curVehicle;
93
94    for (odt = 0; odt < network->numODTs; odt++) {
95      t = network->ODT[odt].departureTime;
96      for (curVehicle = network->ODT[odt].vehicles->head; curVehicle !=
           NULL; curVehicle = curVehicle->next) {
97        latestArrival = max(latestArrival, t + curVehicle->vehicle->path
             ->travelTime);
98      }
99    }
100   return latestArrival * network->tickLength;
101 }
102
103 /* Generate vehicles and data structures after ODTs are complete */
104 void generateVehicles(network_type *network) {
105   int odt, veh;
106   vehicle_type *newVehicle;
107
108   displayMessage(FULL_NOTIFICATIONS, "Generating vehicles...");
109
110   for (odt = 0; odt < network->numODTs; odt++) {
111     for (veh = 0; veh < network->ODT[odt].demand; veh++) {
112       newVehicle = newScalar(vehicle_type);
113       newVehicle->path = NULL;
114       newVehicle->ODT = &(network->ODT[odt]);
115       newVehicle->list = network->origin.cells->head->cell->vehicles;
116       newVehicle->listElt = insertVehicleDoublyLinkedList(network->
             origin.cells->head->cell->vehicles, newVehicle, network->
             origin.cells->head->cell->vehicles->tail);
117       insertVehicleDoublyLinkedList(network->ODT[odt].vehicles,
             newVehicle, network->ODT[odt].vehicles->tail);
118     }
119   }
120
121   displayMessage(FULL_NOTIFICATIONS, "done.\n");
122 }
123
124 void initializeVehicles(network_type *network) {
125    int odt;
126    vehicleDoublyLinkedListElt *curVehicle;
127    path_type *initialPath;
```

```
128
129     for (odt = 0; odt < network->numODTs; odt++) {
130      initialPath = network->ODT[odt].paths->head->path;
131      if (initialPath == NULL) fatalError("No paths available for ODT %d
            -> %d @ %d", network->ODT[odt].origin->ID, network->ODT[odt].
            destination->ID, network->ODT[odt].departureTime);
132        for (curVehicle = network->ODT[odt].vehicles->head; curVehicle !=
               NULL; curVehicle = curVehicle->next) {
133           curVehicle->vehicle->path = initialPath;
134        curVehicle->vehicle->curPathPosition = initialPath->turnMovements
              ->head;
135        }
136     }
137  }
138
139  void prepareAllTrips(network_type *network) {
140     int odt;
141     vehicleDoublyLinkedListElt *curVehicle;
142
143     for (odt = 0; odt < network->numODTs; odt++) {
144        for (curVehicle = network->ODT[odt].vehicles->head; curVehicle !=
               NULL; curVehicle = curVehicle->next) {
145           curVehicle->vehicle->listElt = insertVehicleDoublyLinkedList(
                 network->origin.cells->head->cell->vehicles, curVehicle->
                 vehicle, network->origin.cells->head->cell->vehicles->tail)
                 ;
146           curVehicle->vehicle->list = network->origin.cells->head->cell
                 ->vehicles;
147           curVehicle->vehicle->curPathPosition = curVehicle->vehicle->
                 path->turnMovements->head;
148        }
149     }
150
151  }
152
153  void terminateAllTrips(network_type *network) {
154     int odt;
155     int remainingVehicles = 0;
156     vehicleDoublyLinkedListElt *curVehicle;
157
158     for (odt = 0; odt < network->numODTs; odt++) {
159        for (curVehicle = network->ODT[odt].vehicles->head; curVehicle !=
               NULL; curVehicle = curVehicle->next) {
160          if (curVehicle->vehicle->list != network->destination.cells->
                head->cell->vehicles) remainingVehicles++;
161           deleteVehicleDoublyLinkedListElt(curVehicle->vehicle->list,
                 curVehicle->vehicle->listElt);
```

```
162           curVehicle->vehicle->listElt = insertVehicleDoublyLinkedList(
                 network->destination.cells->head->cell->vehicles,
                 curVehicle->vehicle, network->destination.cells->head->cell
                 ->vehicles->tail);
163           curVehicle->vehicle->list = network->destination.cells->head->
                 cell->vehicles;
164         }
165       }
166
167     if (remainingVehicles > 0) warning(MEDIUM_NOTIFICATIONS, "Simulation
          ended before %d vehicles left network; consider increasing time
          horizon.\n", remainingVehicles);
168   }
169
170   /**** Vehicle doubly linked lists ****/
171
172   vehicleDoublyLinkedList *createVehicleDoublyLinkedList() {
173     declareScalar(vehicleDoublyLinkedList, newdll);
174     newdll->head = NULL;
175     newdll->tail = NULL;
176     newdll->size = 0;
177     return newdll;
178   }
179
180   vehicleDoublyLinkedListElt *insertVehicleDoublyLinkedList(
        vehicleDoublyLinkedList *list, vehicle_type *value,
        vehicleDoublyLinkedListElt *after) {
181     declareScalar(vehicleDoublyLinkedListElt, newNode);
182     newNode->vehicle = value;
183     if (after != NULL) {
184       newNode->prev = after;
185       newNode->next = after->next;
186       if (list->tail != after) newNode->next->prev = newNode; else list->
            tail = newNode;
187       after->next = newNode;
188     } else {
189       newNode->prev = NULL;
190       newNode->next = list->head;
191       if (list->tail != after) newNode->next->prev = newNode; else list->
            tail = newNode;
192       list->head = newNode;
193     }
194     list->size++;
195     return newNode;
196   }
197
198   void deleteVehicleDoublyLinkedList(vehicleDoublyLinkedList *list) {
```

```
199   while (list->head != NULL)
200     deleteVehicleDoublyLinkedListElt(list, list->tail);
201   killScalar(list);
202 }
203
204 void deleteVehicleDoublyLinkedListElt(vehicleDoublyLinkedList *list,
       vehicleDoublyLinkedListElt *elt) {
205   if (list->tail != elt) {
206     if (list->head != elt) elt->prev->next = elt->next; else list->head
          = elt->next;
207     elt->next->prev = elt->prev;
208   } else {
209     list->tail = elt->prev;
210     if (list->head != elt) elt->prev->next = elt->next; else list->head
          = elt->next;
211   }
212   list->size--;
213   killScalar(elt);
214 }
215
216 void displayVehicleDoublyLinkedList(int minVerbosity,
       vehicleDoublyLinkedList *list) {
217   vehicleDoublyLinkedListElt *curnode = list->head;
218   displayMessage(minVerbosity, "Start of the list: %p\n", (void *)list
        ->head);
219   while (curnode != NULL) {
220     displayMessage(minVerbosity, "%p %p %p %p\n", (void *)curnode,
          curnode->vehicle, (void *)curnode->prev, (void *)curnode->next);
221     curnode = (*curnode).next;
222   }
223   displayMessage(minVerbosity, "End of the list: %p\n", (void *)list->
        tail);
224 }
```

D.1.10 vehicle.h

```
1  #ifndef _VEHICLE_H_
2  #define _VEHICLE_H_
3
4  #include "cell.h"
5  #include "datastructures.h"
6  #include "network.h"
7  #include "utils.h"
8  #include "vehicle.h"
9
10 typedef struct vehicle_type_s {
11   path_type *path;
```

```
12    turningLinkedListElt *curPathPosition; /* A pointer to the path's
         turning movement list for next location */
13    ODT_type  *ODT;
14    /* Pointers to list vehicle is stored in (makes for fast moving)
15       Vehicles are *always* a member of a vehicleDoublyLinkedList,
            either waitingVehicles, arrivedVehicles,
16       or a list associated with a link or turning movement */
17    struct vehicleDoublyLinkedList_s    *list;
18    struct vehicleDoublyLinkedListElt_s *listElt;
19  } vehicle_type;
20
21
22  void moveIntralinkVehicles(arc_type *arc);
23  void advanceVehicle(cellDoublyLinkedListElt *curCell);
24  void transferVehicleToLink(vehicle_type *vehicle, turning_type *
       fromMovement, arc_type *toArc, int t); /* Shifts vehicle from
       current location to an arc */
25  void transferVehicleToMovement(vehicle_type *vehicle, arc_type *fromArc
       , turning_type *toMovement, int t); /* Shifts vehicle from current
       location to a movement */
26
27  /**** Vehicle gap functions ****/
28
29  float averageExcessCost(network_type *network);
30  long shortestPathTravelTime(network_type *network);
31  long totalSystemTravelTime(network_type *network);
32  int latestArrivalTime(network_type *network);
33
34  /**** Establish vehicle data structures ****/
35
36  void generateVehicles(network_type *network);
37  void initializeVehicles(network_type *network);
38  void prepareAllTrips(network_type *network);
39  void terminateAllTrips(network_type *network);
40
41  /**** Vehicle doubly linked lists ****/
42
43  typedef struct vehicleDoublyLinkedListElt_s {
44    vehicle_type *vehicle;
45    struct vehicleDoublyLinkedListElt_s *next;
46    struct vehicleDoublyLinkedListElt_s *prev;
47  } vehicleDoublyLinkedListElt;
48
49  typedef struct vehicleDoublyLinkedList_s {
50    vehicleDoublyLinkedListElt *head;
51    vehicleDoublyLinkedListElt *tail;
52    long size;
```

```
53 } vehicleDoublyLinkedList;
54
55 vehicleDoublyLinkedList *createVehicleDoublyLinkedList();
56 vehicleDoublyLinkedListElt *insertVehicleDoublyLinkedList(
      vehicleDoublyLinkedList *list, vehicle_type *value,
      vehicleDoublyLinkedListElt *after);
57 void deleteVehicleDoublyLinkedList(vehicleDoublyLinkedList *list);
58 void deleteVehicleDoublyLinkedListElt(vehicleDoublyLinkedList *list,
      vehicleDoublyLinkedListElt *elt);
59 void displayVehicleDoublyLinkedList(int minVerbosity,
      vehicleDoublyLinkedList *list);
60
61
62 #endif
```

D.1.11 `cell.c`

```
1  #include "cell.h"
2
3  /**** Cell doubly linked lists ****/
4
5
6  /*
7  These functions mirror those in datastructures.h, but for cell doubly
      linked lists.
8  */
9
10 cellDoublyLinkedList *createCellDoublyLinkedList() {
11   declareScalar(cellDoublyLinkedList, newdll);
12   newdll->head = NULL;
13   newdll->tail = NULL;
14   newdll->size = 0;
15   return newdll;
16 }
17
18 cellDoublyLinkedListElt *insertCellDoublyLinkedList(
      cellDoublyLinkedList *list, cell_type *value,
      cellDoublyLinkedListElt *after) {
19   declareScalar(cellDoublyLinkedListElt, newNode);
20   newNode->cell = value;
21   if (after != NULL) {
22     newNode->prev = after;
23     newNode->next = after->next;
24     if (list->head != after) newNode->next->prev = newNode; else list->
         head = newNode;
25     after->next = newNode;
26   } else {
```

```
27      newNode->prev = NULL;
28      newNode->next = list->head;
29      if (list->head != after) newNode->next->prev = newNode; else list->
            head= newNode;
30      list->tail = newNode;
31    }
32    list->size++;
33    return newNode;
34  }
35
36  void deleteCellDoublyLinkedList(cellDoublyLinkedList *list) {
37    while (list->tail != NULL)
38      deleteCellDoublyLinkedListElt(list, list->head);
39    killScalar(list);
40  }
41
42  void deleteCellDoublyLinkedListElt(cellDoublyLinkedList *list,
       cellDoublyLinkedListElt *elt) {
43    if (list->head != elt) {
44      if (list->tail != elt) elt->prev->next = elt->next; else list->tail
            = elt->next;
45      elt->next->prev = elt->prev;
46    } else {
47      list->head = elt->prev;
48      if (list->tail != elt) elt->prev->next = elt->next; else list->tail
            = elt->next;
49    }
50    list->size--;
51    killScalar(elt);
52  }
53
54  void displayCellDoublyLinkedList(int minVerbosity, cellDoublyLinkedList
       *list) {
55    cellDoublyLinkedListElt *curnode = list->head;
56    displayMessage(minVerbosity, "Start of the list: %p\n", (void *)list
         ->head);
57    while (curnode != NULL) {
58      displayMessage(minVerbosity, "%p %p %p %p\n", (void *)curnode,
           curnode->cell, (void *)curnode->prev, (void *)curnode->next);
59      curnode = (*curnode).next;
60    }
61    displayMessage(minVerbosity, "End of the list: %p\n", (void *)list->
         tail);
62  }
```

D.1.12 `cell.h`

```
1  #ifndef _CELL_H_
2  #define _CELL_H_
3
4  #include <math.h>
5  #include "datastructures.h"
6  #include "limits.h"
7  #include "network.h"
8  #include "utils.h"
9
10 struct vehicleDoublyLinkedList_s;
11
12 typedef struct cell_type_s {
13   struct vehicleDoublyLinkedList_s *vehicles;
14   arc_type *parentLink;
15   int sendingFlow;
16   int receivingFlow;
17 } cell_type;
18
19
20 /**** Cell doubly linked lists ****/
21
22 typedef struct cellDoublyLinkedListElt_s {
23   cell_type *cell;
24   struct cellDoublyLinkedListElt_s *next;
25   struct cellDoublyLinkedListElt_s *prev;
26 } cellDoublyLinkedListElt;
27
28 typedef struct cellDoublyLinkedList_s {
29   cellDoublyLinkedListElt *head;
30   cellDoublyLinkedListElt *tail;
31   long size;
32 } cellDoublyLinkedList;
33
34 cellDoublyLinkedList *createCellDoublyLinkedList();
35 cellDoublyLinkedListElt *insertCellDoublyLinkedList(
      cellDoublyLinkedList *list, cell_type *cell, cellDoublyLinkedListElt
       *after);
36 void deleteCellDoublyLinkedList(cellDoublyLinkedList *list);
37 void deleteCellDoublyLinkedListElt(cellDoublyLinkedList *list,
      cellDoublyLinkedListElt *elt);
38 void displayCellDoublyLinkedList(int minVerbosity, cellDoublyLinkedList
       *list);
39
40 #endif
```

D.1.13 network.c

```
1  #include "network.h"
2
3  /**** Network algorithms ****/
4
5  #define ODT_REPORTING_INTERVAL 1000
6  void addShortestPaths(network_type *network) {
7    int odt;
8    pathLinkedListElt *oldPath;
9
10   for (odt = 0; odt < network->numODTs; odt++) {
11     path_type *newPath = createNewPath(network);
12     TDAStar(network, network->ODT[odt].origin, network->ODT[odt].
          destination, network->ODT[odt].departureTime, newPath);
13     /* Does this path already exist? */
14     for (oldPath = network->ODT[odt].paths->head; oldPath != NULL;
          oldPath = oldPath->next) {
15       if (comparePaths(oldPath->path, newPath) == TRUE) break;
16     }
17     if (oldPath == NULL) { /* Path is new, add to relevant lists */
18       insertPathLinkedList(network->paths, newPath, network->paths->
            tail);
19       insertPathLinkedList(network->ODT[odt].paths, newPath, network->
            ODT[odt].paths->tail);
20     } else { /* Path is a duplicate, delete */
21       deletePath(newPath);
22     }
23     if (odt % ODT_REPORTING_INTERVAL == 0) displayMessage(
          FULL_NOTIFICATIONS, "Found new paths for %d of %d ODTs (%d%%)\r"
          , odt, network->numODTs, 100 * odt / network->numODTs);
24   }
25   displayMessage(FULL_NOTIFICATIONS, "Found new paths for %d of %d ODTs
       (%d%%)\n", network->numODTs, network->numODTs, 100);
26
27 }
28
29 /* Time-dependent A* */
30 void TDAStar(network_type *network, node_type *origin, node_type *
      destination, int departureTime, path_type *path) {
31   int ij, s = ptr2node(network, destination);
32   turningLinkedListElt *curMovement;
33   int curArc, tempLabel;
34   declareVector(turning_type *, backMovement, network->numArcs);
35   declareVector(int, label, network->numArcs);
36
37   heap_type *dijkstraHeap = createHeap(network->numArcs, network->
       numArcs);
38
```

```
39     if (origin->ID == 158 && destination->ID == 19 && departureTime ==
          0) verbosity = DEBUG;
40
41   /* Initialization */
42   for (ij = 0; ij < network->numArcs; ij++) {
43     if (network->arc[ij].tail == origin) {
44       dijkstraHeap->valueFn[ij] = min(departureTime + network->arc[ij].
            freeFlowToDest[s], network->timeHorizon);
45       label[ij] = departureTime;
46       for (curMovement = network->arc[ij].upstreamMovements->head;
            curMovement != NULL; curMovement = curMovement->next) {
47         if (curMovement->movement->upstreamArc == &(network->origin))
              break;
48       }
49       if (curMovement != NULL) { /* curMovement would be NULL if there
            are no emanating arcs from origin.  checkNetworkConnectivity
            assures no problems with this. */
50           backMovement[ij] = curMovement->movement;
51           insertHeap(dijkstraHeap, ij, dijkstraHeap->valueFn[ij]);
52         }
53     } else {
54       dijkstraHeap->valueFn[ij] = network->timeHorizon - 1;
55       label[ij] = network->timeHorizon - 1;
56       backMovement[ij] = NULL;
57     }
58   }
59
60   /* Iteration */
61   while (dijkstraHeap->last != NOT_IN_HEAP) {
62     curArc = findMinHeap(dijkstraHeap);
63       displayMessage(DEBUG, "Scanning (%d,%d)\n", network->arc[curArc].
            tail->ID, network->arc[curArc].head->ID);
64     if (network->arc[curArc].head == destination) break;
65     if (label[curArc] + network->arc[curArc].freeFlowToDest[s] >=
          network->timeHorizon) break;
66     deleteMinHeap(dijkstraHeap);
67     for (curMovement = network->arc[curArc].turnMovements->head;
          curMovement != NULL; curMovement = curMovement->next) {
68       if (curMovement->movement->downstreamArc == &(network->
            destination)) continue;
69       displayMessage(DEBUG, "Considering movement %d -> %d -> %d,",
            curMovement->movement->upstreamArc->tail->ID, curMovement->
            movement->downstreamArc->tail->ID, curMovement->movement->
            downstreamArc->head->ID);
70       ij = ptr2arc(network, curMovement->movement->downstreamArc);
71       tempLabel = label[curArc];
72       tempLabel += network->arc[curArc].travelTime[tempLabel];
```

```
73        tempLabel = min(tempLabel, network->timeHorizon - 1);
74        tempLabel += curMovement->movement->travelTime[tempLabel];
75        tempLabel = min(tempLabel, network->timeHorizon - 1);
76        displayMessage(DEBUG, " exact label is %d vs current label %d\n",
              tempLabel, label[ij]);
77        if (tempLabel < label[ij]) {
78          displayMessage(DEBUG, "Noting improvement.\n");
79          label[ij] = tempLabel;
80          if (dijkstraHeap->nodeNDX[ij] == NOT_IN_HEAP) {
81            insertHeap(dijkstraHeap, ij, label[ij] + network->arc[ij].
                 freeFlowToDest[s]);
82            displayMessage(DEBUG, "Adding (%d,%d)\n", network->arc[ij].
                 tail->ID, network->arc[ij].head->ID);
83          } else {
84            decreaseKey(dijkstraHeap, ij, label[ij] + network->arc[ij].
                 freeFlowToDest[s]);
85          }
86          backMovement[ij] = curMovement->movement;
87        }
88      }
89    }
90    if (dijkstraHeap->last == NOT_IN_HEAP) {
91        /* warning(MEDIUM_NOTIFICATIONS, "Unusual termination for A* from
               %d to %d (empty heap but not at destination).  Using free-
             flow path.\n", origin->ID, destination->ID); */
92        curArc = ptr2arc(network, origin->forwardStar->head->arc);
93     }
94
95    /* Now recover path */
96    path->travelTime = min(label[curArc] + network->arc[curArc].
         travelTime[label[curArc]], network->timeHorizon - 1);
97    path->demand = 0;
98    clearTurningLinkedList(path->turnMovements);
99    /* 1. Segment from current arc back to origin */
100   while (network->arc[curArc].tail != origin) {
101     insertTurningLinkedList(path->turnMovements, backMovement[curArc],
          NULL);
102     curArc = ptr2arc(network, backMovement[curArc]->upstreamArc);
103   }
104    insertTurningLinkedList(path->turnMovements, backMovement[curArc],
         NULL);
105   /* 2. Segment from current arc on to destination.
106      This uses the movements based on free-flow times.  This is OK,
           because the 2 regular termination criteria for the A* iteration
            are
107           -> Destination is reached.  In this case, we need to fill in
                 the terminating turn movement, which is same as free-flow
```

```
            movement
108         -> Time horizon is exceeded.  In this case, the path consists
               of the free-flow SP from here on out.
109      For unusual termination (Dijkstra heap being exhausted early), in
          an attempt to recover the program will use the free-flow SP
         and warn the user.
110   */
111    curArc = ptr2arc(network, path->turnMovements->tail->movement->
          downstreamArc);
112    while (path->turnMovements->tail->movement->downstreamArc != &(
          network->destination)) {
113       if (network->arc[curArc].freeFlowMovement[s] == NULL) fatalError(
             "A* is unable to find a path from %d to %d at time %d\n",
             origin->ID, destination->ID, departureTime);
114       insertTurningLinkedList(path->turnMovements, network->arc[curArc
             ].freeFlowMovement[s], path->turnMovements->tail);
115       curArc = ptr2arc(network, network->arc[curArc].freeFlowMovement[s
             ]->downstreamArc);
116    }
117   if (path->turnMovements->tail->movement->downstreamArc != &(network->
         destination)) fatalError("Path from %d to %d at time %d can't
         reach destination", origin->ID, destination->ID, departureTime);
118
119   deleteHeap(dijkstraHeap);
120   deleteVector(backMovement);
121   deleteVector(label);
122
123    displayMessage(DEBUG, "***** Finished iteration *****\n");
124    verbosity = FULL_NOTIFICATIONS;
125 }
126
127 /*
128    Calculate min-cost labels using free-flow times to generate lower
          bounds for A*
129    It's essentially all-to-one label correcting in the dual graph (a
          node for each arc, and an arc for each turning movement)
130    Assume movements have zero travel time for faster LB calculation
131 */
132 void calculateFreeFlowSPLabels(network_type *network, int destination)
       {
133    arcLinkedListElt *curArc;
134    arc_type *upstreamArc;
135    turningLinkedListElt *curMovement;
136    int ij, hi;
137    int tempLabel;
138
139   heap_type *dijkstraHeap = createHeap(network->numArcs, network->
```

```
        numArcs);
140
141     for (ij = 0; ij < network->numArcs; ij++) {
142       dijkstraHeap->valueFn[ij] = INT_MAX; /* value function are the node
              labels.  Need to be much higher than time horizon in case paths
              exceed horizon. */
143       network->arc[ij].freeFlowMovement[destination] = NULL;
144     }
145
146      /* Initialize heap with links terminating at destination */
147      for (curArc = network->node[destination].reverseStar->head; curArc
           != NULL; curArc = curArc->next) {
148         ij = ptr2arc(network, curArc->arc);
149         insertHeap(dijkstraHeap, ij, curArc->arc->numCells);
150         network->arc[ij].freeFlowMovement[destination] = network->arc[ij
              ].turnMovements->head->movement;
151      }
152     while (dijkstraHeap->last != NOT_IN_HEAP) {
153       ij = findMinHeap(dijkstraHeap);
154       deleteMinHeap(dijkstraHeap);
155       for (curMovement = network->arc[ij].upstreamMovements->head;
             curMovement != NULL; curMovement = curMovement->next) {
156           upstreamArc = curMovement->movement->upstreamArc;
157           if (upstreamArc == &(network->origin)) continue;
158           hi = ptr2arc(network, upstreamArc);
159           tempLabel = dijkstraHeap->valueFn[ij] + upstreamArc->numCells;
160           if (tempLabel < dijkstraHeap->valueFn[hi]) {
161              network->arc[hi].freeFlowMovement[destination] =
                    curMovement->movement;
162              if (dijkstraHeap->nodeNDX[hi] == NOT_IN_HEAP) {
163                 insertHeap(dijkstraHeap, hi, tempLabel);
164              } else {
165                 decreaseKey(dijkstraHeap, hi, tempLabel);
166              }
167           }
168       }
169     }
170
171     for (ij = 0; ij < network->numArcs; ij++) {
172         network->arc[ij].freeFlowToDest[destination] = dijkstraHeap->
              valueFn[ij];
173     }
174
175     deleteHeap(dijkstraHeap);
176
177 }
178
```

```
179
180 /*
181 Check zone-to-zone connectivity for OD pairs with positive demand
182 Due to turning movement structure, connectivity check is run in the *
       dual* graph (a node for each arc, and an arc for each turning
       movement))
183 Node reachability checked after arc reachability is determined
184 */
185 void checkNetworkConnectivity(network_type *network) {
186   int ij, origin, destination;
187   declareVector(bool, isNodeReachable, network->numNodes);
188   declareVector(bool, isArcReachable, network->numArcs);
189   queue_type scanList = createQueue(network->numNodes, network->numArcs
         );
190   turningLinkedListElt *curMovement;
191
192   displayMessage(FULL_NOTIFICATIONS, "Checking network connectivity..."
         );
193
194   for (origin = 0; origin < network->numZones; origin++) {
195     /* Initialize */
196     for (destination = 0; destination < network->numNodes; destination
          ++) {
197       isNodeReachable[destination] = FALSE;
198     }
199     for (ij = 0; ij < network->numArcs; ij++) {
200       isArcReachable[ij] = FALSE;
201     }
202     for (curMovement = network->node[origin].turnMovements->head;
          curMovement != NULL; curMovement = curMovement->next) {
203       if (curMovement->movement->upstreamArc == &(network->origin)) {
204         isArcReachable[ptr2arc(network, curMovement->movement->
             downstreamArc)] = TRUE;
205         enQueue(&scanList, ptr2arc(network, curMovement->movement->
             downstreamArc));
206       }
207     }
208
209     /* Identify reachable arcs */
210     while (scanList.curelts > 0) {
211       ij = deQueue(&scanList);
212       for (curMovement = network->arc[ij].turnMovements->head;
           curMovement != NULL; curMovement = curMovement->next) {
213         if (curMovement->movement->downstreamArc == &(network->
             destination)) continue;
214         if (isArcReachable[ptr2arc(network, curMovement->movement->
             downstreamArc)] == FALSE) {
```

```
215             isArcReachable[ptr2arc(network, curMovement->movement->
                   downstreamArc)] = TRUE;
216             enQueue(&scanList, ptr2arc(network, curMovement->movement->
                   downstreamArc));
217           }
218         }
219       }
220
221       /* Identify reachable nodes */
222       for (ij = 0; ij < network->numArcs; ij++) {
223         if (isArcReachable[ij] == TRUE) isNodeReachable[ptr2node(network,
              network->arc[ij].head)] = TRUE;
224       }
225
226
227       /* Warn if positive demand and disconnected graph */
228       for (destination = 0; destination < network->numZones; destination
             ++) {
229         if (isNodeReachable[destination] == FALSE) {
230           if (network->staticOD[origin][destination] > 0) fatalError("
                Origin %d and destination %d are unconnected but have
                positive demand.", origin+1, destination+1);
231         }
232       }
233     }
234     deleteVector(isNodeReachable);
235     deleteVector(isArcReachable);
236     deleteQueue(&scanList);
237
238     displayMessage(FULL_NOTIFICATIONS, "done.\n");
239   }
240
241   bool comparePaths(path_type *path1, path_type *path2) {
242     turningLinkedListElt *curMovement1, *curMovement2;
243
244     /* Easy case */
245     if (pathHash(path1) != pathHash(path2)) return FALSE;
246
247     curMovement1 = path1->turnMovements->head;
248     curMovement2 = path2->turnMovements->head;
249
250     /* Now have to compare movement by movement; they must coincide at
          every movement and end simultaneously */
251     do {
252       if (curMovement1 == NULL && curMovement2 == NULL) return TRUE; /*
            Both end simultaneously */
253       if (curMovement1 == NULL || curMovement2 == NULL) return FALSE; /*
```

```
         One ends before the other */
254      if (curMovement1->movement != curMovement2->movement) return FALSE;
          /* Different movements */
255      curMovement1 = curMovement1->next;
256      curMovement2 = curMovement2->next;
257     } while (TRUE);
258
259   /* Not all movements in common.  Shouldn't reach this point, but here
         to prevent compiler warnings */
260     return FALSE;
261 }
262
263 /* Calculates hashes... involves signed overflow which is undefined
      behavior, but is hopefully treated deterministically */
264 long pathHash(path_type *path) {
265     long hash = 0;
266     turningLinkedListElt *curMovement;
267
268     for (curMovement = path->turnMovements->head; curMovement != NULL;
         curMovement = curMovement->next) {
269      hash += (curMovement->movement->upstreamArc->head->ID * curMovement
          ->movement->downstreamArc->head->ID);
270     }
271
272     return hash;
273 }
274
275
276 /**** Basic network calculations and functions ****/
277
278
279 /* Returning a value greater than the time horizon indicates out-of-
      range (vehicle entering at currentTime can't leave within time
      horizon) */
280 int calculateLinkTravelTime(arc_type *link, int currentTime, int
      timeHorizon) {
281   int t;
282   if (currentTime < 0) return link->numCells;
283   for (t = currentTime + link->numCells; t < timeHorizon; t++) {
284     if (link->downstreamCount[t] >= link->upstreamCount[currentTime])
          return t - currentTime;
285   }
286   return timeHorizon + 1;
287 }
288
289 int calculateMovementTravelTime(turning_type *movement, int currentTime
      , int timeHorizon) {
```

```
290   int t;
291   if (currentTime < 0) return 0;
292   for (t = currentTime; t < timeHorizon; t++) {
293     if (movement->downstreamCount[t] >= movement->upstreamCount[
          currentTime]) return t - currentTime;
294   }
295   return timeHorizon + 1;
296 }
297
298 void calculatePathTravelTime(network_type *network, path_type *path,
       int departureTime) {
299   int t;
300   turningLinkedListElt *curMovement;
301
302   t = departureTime;
303   for (curMovement = path->turnMovements->head; curMovement != NULL;
        curMovement = curMovement->next) {
304     /* Add delay from the movement */
305     t += curMovement->movement->travelTime[t];
306     t = min(t, network->timeHorizon - 1);
307
308     /* Add delay from the next arc */
309     t += curMovement->movement->downstreamArc->travelTime[t];
310     t = min(t, network->timeHorizon - 1);
311   }
312
313   path->travelTime = t - departureTime;
314 }
315
316 /*
317 Copies cumulative counts from one time interval to another.
318 Most commonly used to copy current values when starting a new
      simulation tick
319 ...but could be used more generally.
320 */
321 void copyCounts(network_type *network, int old_t, int new_t) {
322   int i, ij;
323   turningLinkedListElt *curMovement;
324
325   for (ij = 0; ij < network->numArcs; ij++) {
326     network->arc[ij].upstreamCount[new_t] = network->arc[ij].
          upstreamCount[old_t];
327     network->arc[ij].downstreamCount[new_t] = network->arc[ij].
          downstreamCount[old_t];
328   }
329   for (i = 0; i < network->numNodes; i++) {
330     for (curMovement = network->node[i].turnMovements->head;
```

```
          curMovement != NULL; curMovement = curMovement->next) {
331         curMovement->movement->upstreamCount[new_t] = curMovement->
              movement->upstreamCount[old_t];
332         curMovement->movement->downstreamCount[new_t] = curMovement->
              movement->downstreamCount[old_t];
333       }
334     }
335   }
336
337   void displayPath(int minVerbosity, path_type *path) {
338     turningLinkedListElt *curMovement;
339
340     for (curMovement = path->turnMovements->head; curMovement != NULL;
          curMovement = curMovement->next) {
341       displayMessage(minVerbosity, "%d -> %d -> %d", curMovement->
            movement->upstreamArc->tail->ID, curMovement->movement->
            upstreamArc->head->ID, curMovement->movement->downstreamArc->
            head->ID);
342       if (curMovement != NULL) displayMessage(minVerbosity, ", ");
343     }
344   }
345
346   void initializeCounts(network_type *network) {
347     int i, ij, t;
348     turningLinkedListElt *curMovement;
349
350     /* Initialize all counts to zero */
351     for (t = 0; t < network->timeHorizon; t++) {
352       for (ij = 0; ij < network->numArcs; ij++) {
353         network->arc[ij].upstreamCount[t] = 0;
354         network->arc[ij].downstreamCount[t] = 0;
355       }
356       for (i = 0; i < network->numNodes; i++) {
357         for (curMovement = network->node[i].turnMovements->head;
              curMovement != NULL; curMovement = curMovement->next) {
358           curMovement->movement->upstreamCount[t] = 0;
359           curMovement->movement->downstreamCount[t] = 0;
360         }
361       }
362     }
363   }
364
365   void initializeTravelTimes(network_type *network) {
366     int i, ij, t;
367     turningLinkedListElt *curMovement;
368
369     /* Initialize all counts to zero */
```

```
370   for (t = 0; t < network->timeHorizon; t++) {
371     for (ij = 0; ij < network->numArcs; ij++) {
372       network->arc[ij].travelTime[t] = network->arc[ij].numCells;
373     }
374     for (i = 0; i < network->numNodes; i++) {
375       for (curMovement = network->node[i].turnMovements->head;
             curMovement != NULL; curMovement = curMovement->next) {
376         curMovement->movement->travelTime[t] = 0;
377       }
378     }
379   }
380
381   for (t = 0; t < network->timeHorizon; t++) {
382     network->origin.travelTime[t] = 0;
383     network->destination.travelTime[t] = 0;
384   }
385 }
386
387 /* Returns arc array index from pointer to an arc */
388 int ptr2arc(network_type *network, arc_type *arcptr) {
389   return (int) (arcptr - network->arc);
390 }
391
392 /* Returns node array index from pointer to a node */
393 int ptr2node(network_type *network, node_type *nodeptr) {
394   return (int) (nodeptr - network->node);
395 }
396
397 /* Updates all link, movement, and path travel times */
398 #define TRAVEL_TIME_REPORTING_INTERVAL 100
399 #define ODT_REPORTING_INTERVAL 1000
400 void updateAllTravelTimes(network_type *network) {
401   int i, ij, odt, t;
402   turningLinkedListElt *curMovement;
403   pathLinkedListElt *curPath;
404
405   /* Update link and movement times */
406   for (t = 0; t < network->timeHorizon; t++) {
407     for (ij = 0; ij < network->numArcs; ij++) {
408       network->arc[ij].travelTime[t] = calculateLinkTravelTime(&(
            network->arc[ij]), t, network->timeHorizon);
409     }
410     for (i = 0; i < network->numNodes; i++) {
411       for (curMovement = network->node[i].turnMovements->head;
             curMovement != NULL; curMovement = curMovement->next) {
412         curMovement->movement->travelTime[t] =
             calculateMovementTravelTime(curMovement->movement, t,
```

```
            network->timeHorizon);
413       }
414     }
415     if (t % TRAVEL_TIME_REPORTING_INTERVAL == 0) displayMessage(
          FULL_NOTIFICATIONS, "Updated link times for %d of %d ticks (%d
          %%)\r", t, network->timeHorizon, 100 * t / network->timeHorizon)
          ;
416   }
417   displayMessage(FULL_NOTIFICATIONS, "Updated link times for %d of %d
        ticks (%d%%)\n", network->timeHorizon, network->timeHorizon, 100);
418
419   /* Update path labels */
420   for (odt = 0; odt < network->numODTs; odt++) {
421     for (curPath = network->ODT[odt].paths->head; curPath != NULL;
          curPath = curPath->next) {
422       calculatePathTravelTime(network, curPath->path, network->ODT[odt
            ].departureTime);
423     }
424     if (odt % ODT_REPORTING_INTERVAL == 0) displayMessage(
          FULL_NOTIFICATIONS, "Updated path times for %d of %d ODTs (%d%%)
          \r", odt, network->numODTs, 100 * odt / network->numODTs);
425   }
426   displayMessage(FULL_NOTIFICATIONS, "Updated path times for %d of %d
        ODTs (%d%%)\n", network->numODTs, network->numODTs, 100);
427
428
429 }
430
431 /**** Generate data structures ****/
432
433
434 /* Create forward and reverse star lists */
435 void createStarLists(network_type *network) {
436   int i, ij;
437   for (i = 0; i < network->numNodes; i++) {
438     network->node[i].forwardStar = createArcLinkedList();
439     network->node[i].reverseStar = createArcLinkedList();
440   }
441   for (ij = 0; ij < network->numArcs; ij++) {
442     insertArcLinkedList(network->arc[ij].tail->forwardStar, &(network->
          arc[ij]), network->arc[ij].tail->forwardStar->tail);
443     insertArcLinkedList(network->arc[ij].head->reverseStar, &(network->
          arc[ij]), network->arc[ij].head->reverseStar->tail);
444   }
445   displayMessage(FULL_NOTIFICATIONS, "Created forward and reverse star
        lists.\n");
446 }
```

```
447
448 path_type *createNewPath(network_type *network) {
449    path_type *newPath = newScalar(path_type);
450
451    newPath->turnMovements = createTurningLinkedList();
452    newPath->travelTime = network->timeHorizon + 1;
453    newPath->demand = 0;
454
455    return newPath;
456 }
457
458 void deletePath(path_type *path) {
459    deleteTurningLinkedList(path->turnMovements);
460    deleteScalar(path);
461 }
462
463
464 /**** Arc linked lists ****/
465
466 arcLinkedList *createArcLinkedList() {
467   declareScalar(arcLinkedList, newll);
468   newll->head = NULL;
469   newll->tail = NULL;
470   newll->size = 0;
471   return newll;
472 }
473
474 arcLinkedListElt *insertArcLinkedList(arcLinkedList *list, arc_type *
      value, arcLinkedListElt *after) {
475   declareScalar(arcLinkedListElt, newNode);
476   newNode->arc = value;
477   if (after != NULL) { /* Not inserting at head */
478     newNode->next = after->next;
479     if (list->tail == after) list->tail = newNode;
480     after->next = newNode;
481   } else { /* Inserting at head */
482     newNode->next = list->head;
483     if (list->tail == after) list->tail = newNode;
484     list->head = newNode;
485   }
486   list->size++;
487   return newNode;
488 }
489
490 void deleteArcLinkedList(arcLinkedList *list) {
491   arcLinkedListElt *savenode, *curnode = list->head;
492   while (curnode != NULL) {
```

```
493     savenode = curnode->next;
494     killScalar(curnode);
495     curnode = savenode;
496   }
497   killScalar(list);
498 }
499
500 void displayArcLinkedList(int minVerbosity, arcLinkedList *list) {
501   arcLinkedListElt *curnode = list->head;
502   displayMessage(minVerbosity, "Start of the list: %p\n", (void *)list
        ->head);
503   while (curnode != NULL) {
504     displayMessage(minVerbosity, "%p: (%d,%d) -> %p\n", (void *)curnode
          , curnode->arc->tail->ID, curnode->arc->head->ID, (void *)
          curnode->next);
505     curnode = curnode->next;
506   }
507   displayMessage(minVerbosity, "End of the list: %p\n", (void *)list->
        tail);
508 }
509
510 /**** Turning movement linked lists ****/
511
512 turningLinkedList *createTurningLinkedList() {
513   declareScalar(turningLinkedList, newll);
514   newll->head = NULL;
515   newll->tail = NULL;
516   newll->size = 0;
517   return newll;
518 }
519
520 turningLinkedListElt *insertTurningLinkedList(turningLinkedList *list,
      struct turning_type_s *value, turningLinkedListElt *after) {
521   declareScalar(turningLinkedListElt, newNode);
522   newNode->movement = value;
523   if (after != NULL) { /* Not inserting at head */
524     newNode->next = after->next;
525     if (list->tail == after) list->tail = newNode;
526     after->next = newNode;
527   } else { /* Inserting at head */
528     newNode->next = list->head;
529     if (list->tail == after) list->tail = newNode;
530     list->head = newNode;
531   }
532   list->size++;
533   return newNode;
534 }
```

```
535
536 void clearTurningLinkedList(turningLinkedList *list) {
537   turningLinkedListElt *savenode, *curnode = list->head;
538   while (curnode != NULL) {
539     savenode = curnode->next;
540     killScalar(curnode);
541     curnode = savenode;
542   }
543 }
544
545 void deleteTurningLinkedList(turningLinkedList *list) {
546   turningLinkedListElt *savenode, *curnode = list->head;
547   while (curnode != NULL) {
548     savenode = curnode->next;
549     killScalar(curnode);
550     curnode = savenode;
551   }
552   killScalar(list);
553 }
554
555 void displayTurningLinkedList(int minVerbosity, struct
       turningLinkedList_s *list) {
556   turningLinkedListElt *curnode = list->head;
557   displayMessage(minVerbosity, "Start of the list: %p\n", (void *)list
         ->head);
558   while (curnode != NULL) {
559     displayMessage(minVerbosity, "%p: (%d,%d,%d) -> %p\n", (void *)
           curnode, curnode->movement->upstreamArc->tail->ID, curnode->
           movement->upstreamArc->head->ID, curnode->movement->
           downstreamArc->ID, (void *)curnode->next);
560     curnode = curnode->next;
561   }
562   displayMessage(minVerbosity, "End of the list: %p\n", (void *)list->
         tail);
563 }
564
565
566 /**** Path linked lists ****/
567
568 pathLinkedList *createPathLinkedList() {
569   declareScalar(pathLinkedList, newll);
570   newll->head = NULL;
571   newll->tail = NULL;
572   newll->size = 0;
573   return newll;
574 }
575
```

```
576 pathLinkedListElt *insertPathLinkedList(pathLinkedList *list, struct
       path_type_s *value, pathLinkedListElt *after) {
577   declareScalar(pathLinkedListElt, newNode);
578   newNode->path = value;
579   if (after != NULL) { /* Not inserting at head */
580     newNode->next = after->next;
581     if (list->tail == after) list->tail = newNode;
582     after->next = newNode;
583   } else { /* Inserting at head */
584     newNode->next = list->head;
585     if (list->tail == after) list->tail = newNode;
586     list->head = newNode;
587   }
588   list->size++;
589   return newNode;
590 }
591
592 void deletePathLinkedList(pathLinkedList *list) {
593   pathLinkedListElt *savenode, *curnode = list->head;
594   while (curnode != NULL) {
595     savenode = curnode->next;
596     killScalar(curnode);
597     curnode = savenode;
598   }
599   killScalar(list);
600 }
```

D.1.14 network.h

```
1  #ifndef _NETWORK_H_
2  #define _NETWORK_H_
3
4  #include <limits.h>
5  #include <math.h>
6  #include "datastructures.h"
7  #include "utils.h"
8
9  typedef enum {
10   UNKNOWN_CONTROL,
11   CENTROID,
12   NONHOMOGENEOUS,
13   DIVERGE,
14   MERGE,
15   FOUR_WAY_STOP,
16   TWO_WAY_STOP,
17   BASIC_SIGNAL,
18   FANCY_SIGNAL,
```

```
19    INTERCHANGE
20  } intersection_type;
21
22  typedef struct node_type_s {
23    struct arcLinkedList_s     *forwardStar;
24    struct arcLinkedList_s     *reverseStar;
25    struct turningLinkedList_s *turnMovements;
26    intersection_type control;
27    int ID;
28    float X;
29    float Y;
30     void *controlData; /* Pointer to additional information depending on
          intersection type (signal, stop, etc.) */
31  } node_type;
32
33  /*
34  'float's refer to PHYSICAL link characteristics (total link length,
       free flow time) in standard units
35  'int's  refer to CELL characteristics in cell units (timestep, cell
       length)
36  */
37  typedef struct arc_type_s {
38    struct cellDoublyLinkedList_s *cells;
39    struct turningLinkedList_s    *turnMovements;
40    struct turningLinkedList_s    *upstreamMovements;
41    node_type *tail;
42    node_type *head;
43    int *travelTime;      /* [time] */
44    int *upstreamCount;   /* [time] */
45    int *downstreamCount; /* [time] */
46    int *freeFlowToDest;   /* [dest] -- labels for free-flow time to
         destination, to be used in A* */
47    struct turning_type_s **freeFlowMovement; /* [dest] -- movement for
         free-flow time to destination, in case A* exceeds time horizon */
48    float length;
49    float capacity;
50    float jamDensity;
51    float waveRatio;
52    float freeFlowTime;
53    int numCells;
54    int cellCapacity;
55    int cellMaxVehicles;
56    int sendingFlow;
57    int receivingFlow;
58    int ID;
59  } arc_type;
60
```

```
61 typedef struct turning_type_s {
62   struct vehicleDoublyLinkedList_s *vehicles;
63   arc_type *upstreamArc;
64   arc_type *downstreamArc;
65   int *travelTime;      /* [time] */
66   int *upstreamCount;   /* [time] */
67   int *downstreamCount; /* [time] */
68   int targetDelay;
69   int capacity;         /* simulation ticks */
70   float saturationFlow; /* real units */
71   int flow;
72   int sendingFlow;
73   int receivingFlow;
74 } turning_type;
75
76 typedef struct path_type_s {
77   struct turningLinkedList_s *turnMovements;
78   int travelTime;
79   int demand;
80 } path_type;
81
82 typedef struct ODT_type_s {
83   node_type *origin;
84   node_type *destination;
85   int departureTime;
86   int demand;
87   struct vehicleDoublyLinkedList_s *vehicles;
88   struct pathLinkedList_s *paths;
89 } ODT_type;
90
91 typedef struct network_type_s {
92   arc_type  *arc;
93   node_type *node;
94   ODT_type  *ODT;
95   struct pathLinkedList_s *paths;
96   arc_type  origin; /* Artificial origin arc used to store vehicles and
         as upstreamArc for originating turning moveemnts */
97   arc_type  destination; /* Artificial destination arc used to store
        vehicles and as downstreamArc for arrival turning movements */
98   node_type sink; /* Artificial node for origin and destination arc*/
99   float **staticOD; /* [origin][destination] */
100  float totalODFlow;
101  float tickLength;
102  int numArcs;
103  int numNodes;
104  int numZones;
105  long numVehicles;
```

```
106   long numODTs; /* Needs to be of size long = int*int */
107   int timeHorizon; /* In *clock ticks* (compare with parameters_type
          which has time horizon in seconds) */
108   int lastVehicleOn; /* In *clock ticks* (compare with parameters_type
          which has last vehicle on in seconds) */
109 } network_type;
110
111
112 /**** Network algorithms ****/
113
114 void allDestinationsTDSP(network_type *network, path_type *path);
115 void TDAStar(network_type *network, node_type *origin, node_type *
       destination, int departureTime, path_type *path);
116 void calculateFreeFlowSPLabels(network_type *network, int destination);
117 void checkNetworkConnectivity(network_type *network);
118 bool comparePaths(path_type *path1, path_type *path2);
119 long pathHash(path_type *path);
120
121 /**** Basic network calculations and functions ****/
122
123 void addShortestPaths(network_type *network);
124 int calculateLinkTravelTime (arc_type *link, int currentTime, int
       timeHorizon);
125 int calculateMovementTravelTime (turning_type *movement, int
       currentTime, int timeHorizon);
126 void calculatePathTravelTime(network_type *network, path_type *path,
       int departureTime);
127 void copyCounts(network_type *network, int old_t, int new_t);
128 void displayPath(int minVerbosity, path_type *path);
129 void initializeCounts(network_type *network);
130 void initializeTravelTimes(network_type *network);
131 int ptr2arc(network_type *network, arc_type *arcptr);
132 int ptr2node(network_type *network, node_type *nodeptr);
133 void updateAllTravelTimes(network_type *network);
134
135 /**** Network data structures ****/
136
137 path_type *createNewPath(network_type *network);
138 void createStarLists(network_type *network);
139 void deletePath(path_type *path);
140
141 /**** Arc linked lists ****/
142
143 typedef struct arcLinkedListElt_s {
144   arc_type *arc;
145   struct arcLinkedListElt_s *next;
146 } arcLinkedListElt;
```

```
147
148 typedef struct arcLinkedList_s {
149   arcLinkedListElt *head;
150   arcLinkedListElt *tail;
151   int size;
152 } arcLinkedList;
153
154 arcLinkedList *createArcLinkedList();
155 arcLinkedListElt *insertArcLinkedList(arcLinkedList *list, arc_type *
      value, arcLinkedListElt *after);
156 void deleteArcLinkedList(arcLinkedList *list);
157 void displayArcLinkedList(int minVerbosity, arcLinkedList *list);
158
159 /**** Turning movement linked lists ****/
160
161 typedef struct turningLinkedListElt_s {
162   turning_type *movement;
163   struct turningLinkedListElt_s *next;
164 } turningLinkedListElt;
165
166 typedef struct turningLinkedList_s {
167   turningLinkedListElt *head;
168   turningLinkedListElt *tail;
169   int size;
170 } turningLinkedList;
171
172 turningLinkedList *createTurningLinkedList();
173 turningLinkedListElt *insertTurningLinkedList(turningLinkedList *list,
      turning_type *value, turningLinkedListElt *after);
174 void clearTurningLinkedList(turningLinkedList *list);
175 void deleteTurningLinkedList(turningLinkedList *list);
176 void displayTurningLinkedList(int minVerbosity, turningLinkedList *list
      );
177
178 /**** Path linked lists ****/
179
180 typedef struct pathLinkedListElt_s {
181   path_type *path;
182   struct pathLinkedListElt_s *next;
183 } pathLinkedListElt;
184
185 typedef struct pathLinkedList_s {
186   pathLinkedListElt *head;
187   pathLinkedListElt *tail;
188   int size;
189 } pathLinkedList;
190
```

```
191 pathLinkedList *createPathLinkedList();
192 pathLinkedListElt *insertPathLinkedList(pathLinkedList *list, struct
       path_type_s *value, pathLinkedListElt *after);
193 void deletePathLinkedList(pathLinkedList *list);
194
195 #endif
```

D.1.15 sampling.c

```
 1 #include "sampling.h"
 2
 3 /* Factorial table to save computation */
 4 long factorial[10] = {1, 1, 2, 6, 24, 120, 720, 5040, 40320, 362880};
 5
 6 /* Constants used in economized polynomial approximation */
 7 #define A_PRECISION 7
 8 double A[A_PRECISION + 1] = {-0.49999999, 0.33333328, -0.25000678,
       0.20001178, -0.16612694, 0.14218783, -0.13847944, 0.12500596};
 9
10 double randomSample(double mean, double stdev, distribution_type
       distribution) {
11   switch (distribution) {
12   case DETERMINISTIC:
13     return mean;
14   case UNIFORM:
15     return randUniform(mean - stdev * 1.73205080756887729353, mean +
          stdev * 1.73205080756887729353);
16   case POISSON:
17     return randPoisson(mean);
18   case LOGNORMAL:
19     return randLognormalMeanStdev(mean, stdev);
20   case NORMAL:
21     return randNormal(mean, stdev);
22   case EXPONENTIAL:
23     return randExponential(1 / mean);
24   default:
25     fatalError("Unknown distribution type %d\n", distribution);
26   }
27   return 0; /* Should never be reached; included to avoid compiler
        warnings */
28 }
29
30 long randInt(long min, long max) {
31    return min + floor(randUniform(0, max-min));
32 }
33
34 long stochasticRound(double x) {
```

```
35    return floor(x) + (randUniform(0, 1) < x - floor(x) ? 1 : 0);
36 }
37
38
39 /* Poisson sampling procedure from Ahrens and Dieter;
40    variable names and labels taken directly from their paper */
41 #define TOO_HIGH 50
42 long randPoisson(double mu) {
43   double s, d, J, L, T, G, U = 0, E;
44   double omega, b1, b2, c3, c2, c1, c0, c;
45   double px, py, fx, fy;
46   double delta;
47   double V, X;
48   double M, p, q, p0;
49   double P[36];
50   int i;
51   long K = 0;
52   char comingFrom;
53   if (mu >= 10) goto CASE_A;
54   else goto CASE_B;
55
56 CASE_A:
57   s = sqrt(mu);
58   d = 6 * mu * mu;
59   L = floor(mu - 1.1484);
60 /* N: Label indicated in algorithm but not used in code; commented out
      to avoid compiler warnings */
61   T = randNormal(0, 1);
62   G = mu + s * T;
63   if (G >= 0) K = floor(G); else goto P;
64 /* I: Label indicated in algorithm but not used in code; commented out
      to avoid compiler warnings */
65   if (K >= L) return K;
66 /* S: Label indicated in algorithm but not used in code; commented out
      to avoid compiler warnings */
67   U = randUniform(0, 1);
68   if (d * U >= (mu - K) * (mu - K) * (mu - K)) return K;
69 P:
70   omega = 0.39894228 / s;
71   b1 = 0.0416666667 / mu;
72   b2 = 0.3 * b1 * b1;
73   c3 = 0.142857143 * b1 * b2;
74   c2 = b2 - 15 * c3;
75   c1 = b1 - 6 * b2 + 45 * c3;
76   c0 = 1 - b1 + 3 * b2 - 15 * c3;
77   c = 0.1069 / mu;
78   if (G >= 0) { comingFrom = 'P'; goto F; } else goto E;
```

```
Q:
  if (fy * (1 - U) <= py * exp(px - fx)) return K;
E:
  E = randExponential(1);
  U = randUniform(0, 1);
  U = U + U - 1;
  T = 1.8 + E * copysign(1.0, U);
  if (T <= -0.6744) goto E;
  K = floor(mu + s * T);
  comingFrom = 'E';
  goto F;
H:
  if (c * fabs(U) > py * exp(px + E) - fy * exp(fx + E)) goto E;
  return K;
F:
  if (K < 10) {
    px = -mu;
    py = pow(mu, K) / factorial[K];
  } else {
    delta = 0.0833333333 / K;
    delta = delta - 4.8 * pow(delta, 3);
    V = (mu - K) / (double) K;
    if (fabs(V) > 0.25) {
      px = K * log(1 + V) - (mu - K) - delta;
    } else {
      px = A[A_PRECISION];
      for (i = A_PRECISION - 1; i >= 0; i--) {
        px = A[i] + px * V;
      }
      px *= K * V * V;
      px -= delta;
    }
    py = 0.39894228 / sqrt(K);
  }
  X = (K - mu + 0.5) / s;
  fx = -0.5 * X * X;
  fy = omega * (((c3 * X * X + c2) * X * X + c1) * X * X + c0);
  if (comingFrom == 'P') goto Q;
  if (comingFrom == 'E') goto H;
  fatalError("randomPoisson: invalid comingFrom value");

CASE_B:
  if (mu > 1) M = mu; else M = 1;
  L = 0;
  p = exp(-mu);
  q = p;
  p0 = p;
```

```
126   U = randUniform(0, 1);
127 U:
128   K = 0;
129   if (U <= p0) return K;
130 /* T:  Label indicated in algorithm but not used in code; commented out
         to avoid compiler warnings */
131   if (L == 0) goto C;
132   if (U > 0.458) {
133     if (L < M) J = L; else J = M;
134   } else {
135     J = 1;
136   }
137   for (K = J; K <= L; K++) {
138     if (U <= P[K]) return K;
139   }
140   goto U;
141 C:
142   for (K = L + 1; K <= 35; K++) {
143     p = p * mu / (double) K;
144     q = q + p;
145     P[K] = q;
146     if (U <= q) {
147       L = K;
148       return K;
149     }
150   }
151   L = 35;
152   goto U;
153 }
154
155 double randExponential(double lambda) {
156   double d = 1;
157   while (d >= 1) d = randUniform(0, 1);
158   return -log(1 - d) / lambda;
159 }
160
161 double randUniform(double a, double b) {
162   return a + (((double) rand() - 1) / RAND_MAX) * (b - a);
163 }
164
165 double randNormal(double mean, double stdev) {
166   static long numSamples = 0;
167   static double Z2;
168   if ((numSamples++ & 1) == 0) {
169     double Z1, U1, U2;
170     do { U1 = randUniform(0, 1); } while (U1 <= 0 || U1 >= 1);
171     do { U2 = randUniform(0, 1); } while (U1 <= 0 || U1 >= 1);
```

```
172      Z1 = sqrt(-2 * log(U1)) * cos(6.28318531 * U2);
173      Z2 = sqrt(-2 * log(U1)) * sin(6.28318531 * U2);
174      return mean + stdev * Z1;
175    } else {
176      return mean + stdev * Z2;
177    }
178  }
179
180  double randLognormal(double mu, double sigma) {
181    return exp(randNormal(mu, sigma));
182  }
183
184  double randLognormalMeanStdev(double mean, double stdev) {
185    return randLognormal( log(mean) - 0.5 * log(1 + (stdev * stdev) / (
         mean * mean)) , log(1 + (stdev * stdev) / (mean * mean)));
186  }
187
188  /* Create an extra row/col with the "extra bits" left over... calculate
       row/col sums then % precision */
189  void roundStochasticMatrix(float **matrix, int numRows, int numCols,
       int precision) {
190    int bit, row, col;
191    long scaleFactor = 1 << precision, sum;
192    declareMatrix(long, scaledMatrix, numRows + 1, numCols + 1);
193
194    /* Rounding code needs integer values; multiply by appropriate power
         of 2 and cast to int */
195    for (row = 0; row < numRows; row++) {
196       for (col = 0; col < numCols; col++) {
197          matrix[row][col] *= scaleFactor;
198          scaledMatrix[row][col] = round2long(matrix[row][col]);
199       }
200    }
201
202    /* Fill in "remainder" rows and colums to have integer row/column
       sums */
203    for (row = 0; row < numRows; row++) {
204       sum = 0;
205       for (col = 0; col < numCols; col++) {
206          sum += scaledMatrix[row][col];
207       }
208       scaledMatrix[row][numCols] = scaleFactor - sum % scaleFactor;
209    }
210    for (col = 0; col < numCols + 1; col++) {
211       sum = 0;
212       for (row = 0; row < numRows; row++) {
213          sum += scaledMatrix[row][col];
```

```
214         }
215         scaledMatrix[numRows][col] = scaleFactor - sum % scaleFactor;
216      }
217
218
219      /* Now do stochastic rounding, bit by bit */
220      for (bit = 0; bit < precision; bit++) {
221         roundIntegerBit(scaledMatrix, numRows + 1, numCols + 1, bit);
222
223      }
224
225      /* Now undo scaling */
226      for (row = 0; row < numRows; row++) {
227         for (col = 0; col < numCols; col++) {
228            matrix[row][col] = scaledMatrix[row][col] >> precision;
229         }
230      }
231
232      deleteMatrix(scaledMatrix, numRows + 1);
233   }
234
235   /* What happens if there are an odd number of 'bits' ?  algo suggested
        an extra row/col ???
236      Perhaps this is not an issue unless precision is super high */
237   void roundIntegerBit(long **matrix, int numRows, int numCols, int bit)
        {
238      int row, col, switchRow, switchCol, parity;
239      long mask = 1 << bit;
240
241      /* Generate network structure */
242      declareMatrix(int, rowMatch, numRows, numCols);
243      declareMatrix(int, colMatch, numRows, numCols);
244      generateParityNetwork(matrix, rowMatch, colMatch, numRows, numCols,
           mask);
245
246      for (row = 0; row < numRows; row++) {
247         for (col = 0; col < numCols; col++) {
248            if (matrix[row][col] & mask) {
249               switchRow = row;
250               switchCol = col;
251           parity = rand() & 1;
252               do {
253                  switch (parity) {
254                  case 0: /* Set bit to zero and move row-wise*/
255                     matrix[switchRow][switchCol] -= mask;
256                     switchRow = rowMatch[switchRow][switchCol];
257                     break;
```

```
258                case 1: /* Set bit to one and move column-wise */
259                   matrix[switchRow][switchCol] += mask;
260                   switchCol = colMatch[switchRow][switchCol];
261                   break;
262                }
263                parity = 1 - parity;
264             } while (matrix[switchRow][switchCol] & mask);
265          }
266       }
267    }
268
269    deleteMatrix(rowMatch, numRows);
270    deleteMatrix(colMatch, numRows);
271 }
272
273 void generateParityNetwork(long **matrix, int **rowMatch, int **
       colMatch, int numRows, int numCols, long mask) {
274    int row, col, companionRow = IS_MISSING;
275    declareVector(int, companionCol, numRows);
276
277    for (row = 0; row < numRows; row++) {
278       companionCol[row] = IS_MISSING;
279       for (col = 0; col < numCols; col++) {
280          rowMatch[row][col] = IS_MISSING;
281          colMatch[row][col] = IS_MISSING;
282       }
283    }
284
285    for (col = 0; col < numCols; col++) {
286       for (row = 0; row < numRows; row++) {
287          if (matrix[row][col] & mask) {
288             if (companionRow == IS_MISSING) {
289                companionRow = row;
290             } else {
291                rowMatch[row][col] = companionRow;
292                rowMatch[companionRow][col] = row;
293                companionRow = IS_MISSING;
294             }
295             if (companionCol[row] == IS_MISSING) {
296                companionCol[row] = col;
297             } else {
298                colMatch[row][col] = companionCol[row];
299                colMatch[row][companionCol[row]] = col;
300                companionCol[row] = IS_MISSING;
301             }
302          }
303       }
```

```
304     }
305
306     deleteVector(companionCol);
307 }
```

D.1.16 sampling.h

```
1  #ifndef _SAMPLING_H_
2  #define _SAMPLING_H_
3
4  #include <math.h>
5  #include <stdlib.h>
6  #include "datastructures.h"
7  #include "utils.h"
8
9  typedef enum {
10   DETERMINISTIC,
11   UNIFORM,
12   POISSON,
13   NORMAL,
14   EXPONENTIAL,
15   LOGNORMAL,
16   UNKNOWN_DISTRIBUTION
17 } distribution_type;
18
19
20 /* Random number generation */
21
22 double randomSample(double mean, double stdev, distribution_type
       distribution);
23
24 long randInt(long min, long max);
25 long randPoisson(double mu);
26 double randExponential(double lambda);
27 double randUniform(double a, double b);
28 double randNormal(double mean, double stdev);
29 double randLognormal(double mu, double sigma);
30 double randLognormalMeanStdev(double mean, double stdev);
31
32 long stochasticRound(double x);
33
34 /* Stochastic rounding */
35
36 long roundStochastic(double x);
37 void roundStochasticMatrix(float **matrix, int numRows, int numCols,
       int precision); /* Preserves row and column sums with stochastic
       rounding */
```

```
38 void roundIntegerBit(long **matrix, int numRows, int numCols, int bit);
39 void generateParityNetwork(long **matrix, int **rowMatch, int **
      colMatch, int numRows, int numCols, long mask);
40
41 #endif
```

D.1.17 datastructures.c

```
 1 #include "datastructures.h"
 2
 3 /*
 4 This file contains implementation for commonly-used data structures,
      including
 5 singly and doubly linked lists, binary heaps, queues, as well as memory
       allocation
 6 and deallocation.
 7 */
 8
 9 /******************
10  ** Linked lists **
11  ******************/
12
13 /**** Singly linked lists ****/
14
15 linkedList *createLinkedList() {
16   declareScalar(linkedList, newll);
17   newll->head = NULL;
18   newll->tail = NULL;
19   newll->size = 0;
20   return newll;
21 }
22
23 linkedListElt *insertLinkedList(linkedList *list, int value,
      linkedListElt *after) {
24   declareScalar(linkedListElt, newNode);
25   newNode->value = value;
26   if (after != NULL) { /* Not inserting at head */
27     newNode->next = after->next;
28     if (list->tail == after) list->tail = newNode;
29     after->next = newNode;
30   } else { /* Inserting at head */
31     newNode->next = list->head;
32     if (list->tail == after) list->tail = newNode;
33     list->head = newNode;
34   }
35   list->size++;
36   return newNode;
```

```
37 }
38
39 void deleteLinkedList(linkedList *list) {
40   linkedListElt *savenode, *curnode = list->head;
41   while (curnode != NULL) {
42     savenode = curnode->next;
43     killScalar(curnode);
44     curnode = savenode;
45   }
46   killScalar(list);
47 }
48
49 void displayLinkedList(int minVerbosity, linkedList *list) {
50   linkedListElt *curnode = list->head;
51   displayMessage(minVerbosity, "Start of the list: %p\n", (void *)list
       ->head);
52   while (curnode != NULL) {
53     displayMessage(minVerbosity, "%p: %d -> %p\n", (void *)curnode,
         curnode->value, (void *)curnode->next);
54     curnode = curnode->next;
55   }
56   displayMessage(minVerbosity, "End of the list: %p\n", (void *)list->
       tail);
57 }
58
59 /**** Doubly linked lists ****/
60
61 doublyLinkedList *createDoublyLinkedList() {
62   declareScalar(doublyLinkedList, newdll);
63   newdll->head = NULL;
64   newdll->tail = NULL;
65   newdll->size = 0;
66   return newdll;
67 }
68
69 doublyLinkedListElt *insertDoublyLinkedList(doublyLinkedList *list,
     double value, doublyLinkedListElt *after) {
70   declareScalar(doublyLinkedListElt, newNode);
71   newNode->value = value;
72   if (after != NULL) {
73     newNode->prev = after;
74     newNode->next = after->next;
75     if (list->tail != after) newNode->next->prev = newNode; else list->
         tail = newNode;
76     after->next = newNode;
77   } else {
78     newNode->prev = NULL;
```

```
79      newNode->next = list->head;
80      if (list->tail != after) newNode->next->prev = newNode; else list->
            tail = newNode;
81      list->head = newNode;
82    }
83    list->size++;
84    return newNode;
85  }
86
87  void deleteDoublyLinkedList(doublyLinkedList *list) {
88    while (list->head != NULL)
89      deleteDoublyLinkedListElt(list, list->tail);
90    killScalar(list);
91  }
92
93  void deleteDoublyLinkedListElt(doublyLinkedList *list,
        doublyLinkedListElt *elt) {
94    if (list->tail != elt) {
95      if (list->head != elt) elt->prev->next = elt->next; else list->head
            = elt->next;
96      elt->next->prev = elt->prev;
97    } else {
98      list->tail = elt->prev;
99      if (list->head != elt) elt->prev->next = elt->next; else list->head
            = elt->next;
100   }
101   list->size--;
102   killScalar(elt);
103 }
104
105 void displayDoublyLinkedList(int minVerbosity, doublyLinkedList *list)
        {
106   doublyLinkedListElt *curnode = list->head;
107   displayMessage(minVerbosity, "Start of the list: %p\n", (void *)list
          ->head);
108   while (curnode != NULL) {
109     displayMessage(minVerbosity, "%p %f %p %p\n", (void *)curnode,
          curnode->value, (void *)curnode->prev, (void *)curnode->next);
110     curnode = (*curnode).next;
111   }
112   displayMessage(minVerbosity, "End of the list: %p\n", (void *)list->
          tail);
113 }
114
115 /************
116  ** Queues **
117  ************/
```

```
118
119 /**** Standard queue with memory ****/
120
121 queue_type createQueue(long size, long eltsize) {
122   long i;
123
124   queue_type queue;
125   queue.node = newVector(size, long);
126   queue.history = newVector(eltsize, char);
127   queue.readptr = 0;
128   queue.writeptr = 0;
129   queue.size = size;
130   queue.curelts = 0;
131
132   for (i = 0; i < eltsize; i++) queue.history[i] = NEVER_IN_QUEUE;
133   for (i = 0; i < size; i++) queue.node[i] = 0;
134   return queue;
135 }
136
137 void deleteQueue(queue_type *queue) {
138   deleteVector(queue->node);
139   deleteVector(queue->history);
140 }
141
142 void enQueue(queue_type *queue, long elt) {
143   if (queue->history[elt] == IN_QUEUE) return;
144   if (queue->curelts == queue->size) fatalError("Queue not large enough
        !");
145   queue->curelts++;
146   queue->node[queue->writeptr] = elt;
147   queue->writeptr++;
148   if (queue->writeptr == queue->size) queue->writeptr = 0;
149   queue->history[elt] = IN_QUEUE;
150 }
151
152 void frontQueue(queue_type *queue, long elt) {
153   if (queue->history[elt] == IN_QUEUE) return;
154   if (queue->readptr == 0) queue->readptr = queue->size; else queue->
        readptr--;
155   if (queue->curelts == queue->size) fatalError("Queue not large enough
        !");
156   queue->curelts++;
157   queue->node[queue->readptr] = elt;
158   queue->history[elt] = IN_QUEUE;
159 }
160
161 long deQueue(queue_type *queue) {
```

```
162   long val = queue->node[queue->readptr];
163   queue->history[queue->node[queue->readptr]] = WAS_IN_QUEUE;
164   queue->readptr++;
165   queue->curelts--;
166   if (queue->readptr >= queue->size) queue->readptr = 0;
167   return val;
168 }
169
170 void displayQueue(int minVerbosity, queue_type *queue) {
171   long i;
172   for (i = 0; i < queue->size; i++) {
173     displayMessage(minVerbosity, "%ld ", queue->node[i]);
174     if (i == queue->readptr) displayMessage(minVerbosity, "R"); else
          displayMessage(minVerbosity, " ");
175     if (i == queue->writeptr) displayMessage(minVerbosity, "W"); else
          displayMessage(minVerbosity, " ");
176     displayMessage(minVerbosity, "   %ld %d", i, queue->history[i]);
177     displayMessage(minVerbosity, "\n");
178   }
179 }
180
181
182 /******************
183  ** Binary heaps **
184  ******************/
185
186 heap_type *createHeap(int heapsize, int eltsize) {
187
188   int i;
189   declareScalar(heap_type, newHeap);
190   newHeap->node = newVector(heapsize, int);
191   newHeap->nodeNDX = newVector(eltsize, int);
192   newHeap->last = NOT_IN_HEAP;
193   newHeap->valueFn = newVector(eltsize, int);
194   newHeap->maxsize = heapsize;
195   newHeap->maxelts = eltsize;
196
197   for(i = 0; i < eltsize; i++) newHeap->nodeNDX[i] = NOT_IN_HEAP;
198   return newHeap;
199 }
200
201 void insertHeap(heap_type *heap, int key, int value) {
202   int elt = ++(heap->last);
203   if (heap->last >= heap->maxsize) fatalError("Heap not big enough.");
204   heap->node[heap->last] = key;
205   heap->nodeNDX[key] = heap->last;
206   heap->valueFn[key] = value;
```

```
207   siftUp(heap, elt);
208 }
209
210 int findMinHeap(heap_type *heap) {
211   return heap->node[0];
212 }
213
214 void deleteMinHeap(heap_type *heap) {
215   if (heap->last < 0) fatalError("Negative heap size!");
216   heap->nodeNDX[heap->node[heap->last]] = 0;
217   heap->nodeNDX[heap->node[0]] = NOT_IN_HEAP;
218   if (heap->last > 0) swap(heap->node[0], heap->node[heap->last]);
219   heap->last--;
220   if (heap->last >= 0) siftDown(heap, 1);
221 }
222
223 void deleteHeap(heap_type *heap) {
224   deleteVector(heap->node);
225   deleteVector(heap->nodeNDX);
226   deleteVector(heap->valueFn);
227   deleteScalar(heap);
228 }
229
230 void decreaseKey(heap_type *heap, int elt, int value) {
231   heap->valueFn[heap->node[heap->nodeNDX[elt]]] = value;
232   siftUp(heap, heap->nodeNDX[elt]);
233 }
234
235 void increaseKey(heap_type *heap, int elt, int value) {
236   heap->valueFn[heap->node[heap->nodeNDX[elt]]] = value;
237   siftDown(heap, heap->nodeNDX[elt]);
238 }
239
240 void siftUp(heap_type *heap, int elt) {
241   while (elt > 0 && heap->valueFn[heap->node[elt]] < heap->valueFn[heap
        ->node[heapPred(elt)]]) {
242     swap(heap->nodeNDX[heap->node[elt]], heap->nodeNDX[heap->node[
          heapPred(elt)]]);
243     swap(heap->node[elt], heap->node[heapPred(elt)]);
244     elt = heapPred(elt);
245   }
246 }
247
248 void siftDown(heap_type *heap, int elt) {
249   int tmp;
250   while (heapSucc(elt) <= heap->last && heap->valueFn[heap->node[elt]]
        > heap->valueFn[heap->node[minChild(heap, elt)]]) {
```

```
251       tmp = minChild(heap, elt);
252       swap(heap->nodeNDX[heap->node[elt]], heap->nodeNDX[heap->node[tmp
              ]]);
253       swap(heap->node[elt], heap->node[tmp]);
254       elt = tmp;
255     }
256   }
257
258   int heapPred(int elt) {
259     return (elt - 1) / 2;
260   }
261
262   int heapSucc(int elt) {
263     return (elt * 2) + 1;
264   }
265
266   int minChild(heap_type *heap, int elt) {
267     if (heapSucc(elt) == heap->last)
268       return heap->last;
269     if (heap->valueFn[heap->node[heapSucc(elt)]] <= heap->valueFn[heap->
          node[heapSucc(elt) + 1]])
270       return heapSucc(elt);
271     return heapSucc(elt) + 1;
272   }
273
274   void heapify(heap_type *heap) {
275     long i;
276     for (i = heapPred(heap->last); i >= 0; i--)
277       siftDown(heap, i);
278   }
279
280   void displayHeap(int minVerbosity, heap_type *heap) {
281     int i;
282     displayMessage(minVerbosity, "HEAP current size, capacity, number of
            elements: %d %d %d\n", heap->last, heap->maxsize, heap->maxelts);
283     displayMessage(minVerbosity, "HEAP STATUS");
284     for (i = 0; i < heap->maxsize; i++) {
285       displayMessage(minVerbosity, "\n%d %d", i, heap->node[i]);
286       if (i == heap->last) displayMessage(minVerbosity, " LAST");
287     }
288     displayMessage(minVerbosity, "\nNODE NDX");
289     for (i = 1; i <= heap->maxelts; i++)
290       displayMessage(minVerbosity, "\n%d %d", i, heap->nodeNDX[i]);
291     displayMessage(minVerbosity, "\nVALUE FUNCTION");
292     for (i = 1; i <= heap->maxelts; i++)
293       displayMessage(minVerbosity, "\n%d %f", i, heap->valueFn[i]);
294   }
```

```
295
296 /*************************
297  ** Memory (de)allocation **
298  *************************/
299
300
301 void *allocateScalar(size_t size) {
302   void *scalar = malloc(size);
303   if (scalar == NULL) fatalError("Unable to allocate memory for a
        scalar.");
304   #ifdef MEMCHECK
305   memcheck_numScalars++;
306   if (memcheck_numScalars > MEMCHECK_THRESHOLD) { displayMessage(DEBUG,
         "Now have %ld scalars.\n", memcheck_numScalars); }
307   #endif
308   return scalar;
309 }
310
311 void *allocateVector(long u, size_t size) {
312   void *vector = malloc(u * size);
313   if (vector == NULL) fatalError("Unable to allocate memory for vector
        of size %ld.", u);
314   #ifdef MEMCHECK
315   memcheck_numVectors++;
316   if (memcheck_numVectors > MEMCHECK_THRESHOLD) { displayMessage(DEBUG,
         "Now have %ld vectors.\n", memcheck_numVectors); }
317   #endif
318   return vector;
319 }
320
321 void **allocateMatrix(long u1, long u2, size_t size) {
322   long i;
323   void **matrix = malloc(u1 * sizeof(void *));
324   if (matrix == NULL) fatalError("Unable to allocate memory for matrix
        of size %ld x %ld.", u1, u2);
325   for (i = 0; i < u1; i++) {
326     matrix[i] = malloc(u2 * size);
327     if (matrix[i] == NULL) fatalError("Unable to allocate memory for
          matrix of size %ld x %ld.", u1, u2);
328   }
329   #ifdef MEMCHECK
330   memcheck_numMatrices++;
331   if (memcheck_numMatrices > MEMCHECK_THRESHOLD) { displayMessage(DEBUG
        , "Now have %ld matrices.\n", memcheck_numMatrices); }
332   #endif
333   return matrix;
334 }
```

```
335
336 void ***allocate3DArray(long u1, long u2, long u3, size_t size) {
337   long i, j;
338   void ***matrix = malloc(u1 * sizeof(void **));
339   if (matrix == NULL) fatalError("Unable to allocate 3D array of size %
        ld x %ld x %ld.", u1, u2, u3);
340   for (i = 0; i < u1; i++) {
341     matrix[i] = malloc(u2 * sizeof(void *));
342     if (matrix[i] == NULL) fatalError("Unable to allocate 3D array of
          size %ld x %ld x %ld.", u1, u2, u3);
343     for (j = 0; j < u2; j++) {
344       matrix[i][j] = malloc(u3 * size);
345       if (matrix[i][j] == NULL) fatalError("Unable to allocate 3D array
            of size %ld x %ld x %ld.", u1, u2, u3);
346     }
347   }
348   #ifdef MEMCHECK
349   memcheck_num3DArrays++;
350   if (memcheck_num3DArrays > MEMCHECK_THRESHOLD) { displayMessage(DEBUG
        , "Now have %ld 3D arrays.\n", memcheck_num3DArrays); }
351   #endif
352   return matrix;
353 }
354
355 void killScalar(void *scalar) {
356   free(scalar);
357   #ifdef MEMCHECK
358   memcheck_numScalars--;
359   if (memcheck_numScalars > MEMCHECK_THRESHOLD) { displayMessage(DEBUG,
         "Now have %ld scalars.\n", memcheck_numScalars);  }
360   #endif
361 }
362
363 void killVector(void *vector) {
364   free(vector);
365   #ifdef MEMCHECK
366   memcheck_numVectors--;
367   if (memcheck_numVectors > MEMCHECK_THRESHOLD) { displayMessage(DEBUG,
         "Now have %ld vectors.\n", memcheck_numVectors); }
368   #endif
369 }
370
371 void killMatrix(void **matrix, long u1) {
372   long i;
373   for (i = 0; i < u1; i++) free(matrix[i]);
374   free(matrix);
375   #ifdef MEMCHECK
```

```
376   memcheck_numMatrices--;
377   if (memcheck_numMatrices > MEMCHECK_THRESHOLD) { displayMessage(DEBUG
          , "Now have %ld matrices.\n", memcheck_numMatrices); }
378   #endif
379 }
380
381 void kill3DArray(void ***array, long u1, long u2) {
382   long i, j;
383   for (i = 0; i < u1; i++) {
384     for (j = 0; j < u2; j++) {
385       free(array[i][j]);
386     }
387     free(array[i]);
388   }
389   free(array);
390   #ifdef MEMCHECK
391   memcheck_num3DArrays--;
392   if (memcheck_num3DArrays > MEMCHECK_THRESHOLD) { displayMessage(DEBUG
          , "Now have %ld 3D arrays.\n", memcheck_num3DArrays); }
393   #endif
394 }
```

D.1.18 datastructures.h

```
1  #ifndef _DATASTRUCTURES_H_
2  #define _DATASTRUCTURES_H_
3
4  #include <stdio.h>
5  #include <stdlib.h>
6  #include "utils.h"
7
8
9
10 /******************
11  ** Linked lists **
12  ******************/
13
14 /***** Singly linked lists *****/
15
16 typedef struct linkedListElt_s {
17   int value;
18   struct linkedListElt_s *next;
19 } linkedListElt;
20
21 typedef struct {
22   linkedListElt *head;
23   linkedListElt *tail;
```

```
24    long size;
25  } linkedList;
26
27  linkedList *createLinkedList();
28  linkedListElt *insertLinkedList(linkedList *list, int value,
       linkedListElt *after);
29  void deleteLinkedList(linkedList *list);
30  void displayLinkedList(int minVerbosity, linkedList *list);
31
32  /**** Doubly linked lists ****/
33
34  typedef struct doublyLinkedListElt_s {
35    double value;
36    struct doublyLinkedListElt_s *next;
37    struct doublyLinkedListElt_s *prev;
38  } doublyLinkedListElt;
39
40  typedef struct {
41    doublyLinkedListElt *head;
42    doublyLinkedListElt *tail;
43    long size;
44  } doublyLinkedList;
45
46  doublyLinkedList *createDoublyLinkedList();
47  doublyLinkedListElt *insertDoublyLinkedList(doublyLinkedList *list,
       double value, doublyLinkedListElt *after);
48  void deleteDoublyLinkedList(doublyLinkedList *list);
49  void deleteDoublyLinkedListElt(doublyLinkedList *list,
       doublyLinkedListElt *elt);
50  void displayDoublyLinkedList(int minVerbosity, doublyLinkedList *list);
51
52
53  /************
54   ** Queues **
55   ************/
56
57  /**** Standard queue with memory ****/
58
59  enum {
60    IN_QUEUE,
61    WAS_IN_QUEUE,
62    NEVER_IN_QUEUE
63  };
64
65  typedef enum {
66    DEQUE,
67    FIFO,
```

```
68    LIFO
69  } queueDiscipline;
70
71  typedef struct {
72    long* node;
73    char* history;
74    long readptr;
75    long writeptr;
76    long size;
77    long curelts;
78  } queue_type;
79
80  queue_type createQueue(long size, long eltsize);
81  void deleteQueue(queue_type *queue);
82  void enQueue(queue_type *queue, long elt);
83  void frontQueue(queue_type *queue, long elt);
84  long deQueue(queue_type *queue);
85  void displayQueue(int minVerbosity, queue_type *queue);
86
87  /******************
88   ** Binary heaps **
89   ******************/
90
91  #define NOT_IN_HEAP -1
92
93  typedef struct {
94    int* node;
95    int last;
96    int* valueFn;
97    int* nodeNDX;
98    int maxsize;
99    int maxelts;
100 } heap_type;
101
102 heap_type *createHeap(int heapsize, int eltsize);
103 void insertHeap(heap_type *heap, int key, int value) ;
104 int  findMinHeap(heap_type *heap);
105 void deleteMinHeap(heap_type *heap);
106 void deleteHeap(heap_type *heap);
107 void decreaseKey(heap_type *heap, int elt, int value);
108 void increaseKey(heap_type *heap, int elt, int value);
109 void siftUp(heap_type *heap, int elt);
110 void siftDown(heap_type *heap, int elt);
111 int  heapPred(int elt);
112 int  heapSucc(int elt);
113 int  minChild(heap_type *heap, int elt);
114 void heapify(heap_type *heap);
```

```
115 void displayHeap(int minVerbosity, heap_type *heap);
116
117 /*************************
118  ** Memory (de)allocation **
119  *************************/
120
121
122 /* Comment out this line to disable memory leak checking */
123 /* #define MEMCHECK */
124 #define MEMCHECK_THRESHOLD 1000 /* Threshold before reporting data
       structure counts for memory leak checking */
125
126 void *allocateScalar(size_t size);
127 void *allocateVector(long u, size_t size);
128 void **allocateMatrix(long u1, long u2, size_t size);
129 void ***allocate3DArray(long u1, long u2, long u3, size_t size);
130 void killScalar(void *scalar);
131 void killVector(void *vector);
132 void killMatrix(void **matrix, long u1);
133 void kill3DArray(void ***array, long u1, long u2);
134
135 #define newScalar(y)              (y *)allocateScalar(sizeof(y))
136 #define newVector(u,y)            (y *)allocateVector(u,sizeof(y))
137 #define newMatrix(u1,u2,y)          (y **)allocateMatrix(u1,u2,sizeof(y
       ))
138 #define new3DArray(u1,u2,u3,y)      (y ***)allocate3DArray(u1,u2,u3,
       sizeof(y))
139
140 #define declareScalar(y,S)          y *S = newScalar(y)
141 #define declareVector(y,V,u)        y *V = newVector(u,y)
142 #define declareMatrix(y,M,u1,u2)      y **M = newMatrix(u1,u2,y)
143 #define declare3DArray(y,A,u1,u2,u3)  y ***A = new3DArray(u1,u2,u3,y)
144
145 #define deleteScalar(y)           killScalar(y)
146 #define deleteVector(y)           killVector(y)
147 #define deleteMatrix(y,u1)          killMatrix((void **)y,u1)
148 #define delete3DArray(y,u1,u2)      kill3DArray((void ***)y,u1,u2)
149
150 #ifdef MEMCHECK
151 long memcheck_numScalars, memcheck_numVectors, memcheck_numMatrices,
       memcheck_num3DArrays;
152 #endif
153
154 #endif
```

D.1.19 `utils.c`

```
1  #include "utils.h"
2
3  void waitForKey() {
4    getchar();
5  }
6
7  void SWAP(void* a, void* b, int size) {
8    void* c = malloc(size);
9    memcpy(c, a, size);
10   memcpy(a, b, size);
11   memcpy(b, c, size);
12   free(c);
13 }
14
15 double updateElapsedTime(clock_t startTime, double *elapsedTime) {
16   *elapsedTime += ((double) (clock() - startTime)) / CLOCKS_PER_SEC;
17   return *elapsedTime;
18 }
19
20 /*********************
21  ** Status messages **
22  *********************/
23
24 void displayMessage(int minVerbosity, char *format, ...) {
25   va_list message;
26   if (verbosity < minVerbosity) return;
27   if (minVerbosity < DEBUG) {
28     va_start(message, format);
29     vprintf(format, message);
30     va_end(message);
31     fflush(stdout);
32   }
33   #ifdef DEBUG_MODE
34     va_start(message, format);
35     vfprintf(debugFile, format, message);
36     va_end(message);
37     fflush(debugFile);
38   #endif
39 }
40
41 void fatalError(char *format, ...) {
42   va_list message;
43   va_start(message, format);
44   printf("Fatal error: ");
45   vprintf(format, message);
46   va_end(message);
47   fflush(stdout);
```

```
48    #ifdef DEBUG_MODE
49      va_start(message, format);
50      fprintf(debugFile, "Fatal error: ");
51      vfprintf(debugFile, format, message);
52      va_end(message);
53      fflush(debugFile);
54    #endif
55    if (PAUSE_ON_ERROR == TRUE) waitForKey();
56    #ifdef DEBUG_MODE
57      fclose(debugFile);
58    #endif
59    exit(EXIT_FAILURE);
60  }
61
62  void warning(int minVerbosity, char *format, ...) {
63    va_list message;
64    if (verbosity < minVerbosity) return;
65    va_start(message, format);
66    printf("Warning: ");
67    vprintf(format, message);
68    va_end(message);
69    fflush(stdout);
70    #ifdef DEBUG_MODE
71      va_start(message, format);
72      fprintf(debugFile, "Warning: ");
73      vfprintf(debugFile, format, message);
74      va_end(message);
75      fflush(debugFile);
76    #endif
77    if (PAUSE_ON_WARNING == TRUE) waitForKey();
78  }
```

D.1.20 utils.h

```
1   #ifndef _UTILS_H_
2   #define _UTILS_H_
3
4   #include <string.h>
5   #include <stdarg.h>
6   #include <stdio.h>
7   #include <stdlib.h>
8   #include <time.h>
9
10  #define DEBUG_MODE /* Uncomment this line to echo output to log file.
        */
11
12  #define IS_MISSING -1
```

```
13 #define STRING_SIZE 9999
14
15 #define PAUSE_ON_ERROR FALSE
16 #define PAUSE_ON_WARNING FALSE
17
18
19 /*
20 Standard units: feet, seconds
21 Multiplying a quantity by these values will convert it to standard
      units
22 Dividing a quantity by these values will convert it from standard units
23 */
24 #define HOURS      3600.0
25 #define MINUTES    60.0
26 #define SECONDS    1.0
27 #define MILES      5280.0
28 #define KILOMETERS 3280.839895
29 #define METERS     3.280839895
30 #define FEET       1.0
31 #define INCHES     0.083333333
32
33 #define min(x,y)  ( ((x)<(y)) ? (x) : (y) )
34 #define max(x,y)  ( ((x)>(y)) ? (x) : (y) )
35 #define swap(a,b) SWAP(&a, &b, sizeof(a))
36 #define round2int(x)  (int)((x) < 0 ? ((x) - 0.5) : ((x) + 0.5))
37 #define round2long(x)  (long)((x) < 0 ? ((x) - 0.5) : ((x) + 0.5))
38
39 #ifndef __cplusplus
40 typedef enum {
41   FALSE,
42   TRUE
43 } bool;
44 #endif
45
46 #ifdef DEBUG_MODE
47   char debugFileName[STRING_SIZE];
48   FILE *debugFile;
49 #endif
50
51
52 enum { /* Verbosity levels for status messages */
53   NOTHING,
54   LOW_NOTIFICATIONS,
55   MEDIUM_NOTIFICATIONS,
56   FULL_NOTIFICATIONS,
57   DEBUG,
58   FULL_DEBUG
```

```
59 };
60
61
62 int verbosity;
63
64
65 #ifdef MEMCHECK
66 extern long memcheck_numScalars, memcheck_numVectors,
      memcheck_numMatrices;
67 #endif
68
69 void waitForKey();
70 void SWAP(void *a, void *b, int size);
71 double updateElapsedTime(clock_t startTime, double *elapsedTime);
72
73 /*********************
74  ** Status messages **
75  *********************/
76
77 void displayMessage(int minVerbosity, char *format, ...);
78 void fatalError(char *format, ...);
79 void warning(int minVerbosity, char *format, ...);
80
81 #endif
```

D.2 Warrants module

D.2.1 main_warrant.c

```
1  #include "main_warrant.h"
2
3  int main(int numArgs, char *args[]) {
4     #ifdef DEBUG_MODE /* Debug mode enables extra logging.  Define this
         macro in utils.h */
5        debugFile = openFile("logfile.txt", "w");
6        verbosity = DEBUG;
7        displayMessage(DEBUG, "Starting new run.\n");
8     #endif
9
10    switch (numArgs) {
11    case 5: /* Comprehensive warrant analysis */
12       generateWarrantNodeControls(args[1], args[2], args[3], args[4]);
13       break;
14    case 4: /* Analysis of selected nodes only */
15       {
16          parameters_type run;
```

```
17          FILE *controlFile = openFile(args[3], "w");
18
19          initializeDTARun(&run, args[1]);
20          readCumulativeCounts(run.network, run.countsFileName);
21          analyzeNode(&run, atof(args[2]) - 1);
22          writeNode(controlFile, run.network, atof(args[2]) - 1);
23          cleanUpDTARun(&run);
24          fclose(controlFile);
25          break;
26       }
27    default:
28       displayUsage();
29    }
30
31    #ifdef DEBUG_MODE
32       fclose(debugFile);
33    #endif
34
35    return EXIT_SUCCESS;
36 }
37
38 void displayUsage() {
39    printf("Error in arguments -- two possible usages:\n");
40    printf("\n");
41    printf("Usage 1: To perform a complete run when there is no summary
         file already available:\n");
42    printf("   warrant parametersFile networkFile initialICF finalICF\n"
         );
43    printf("      parametersFile - standard parameters file for
         executing calibrating run\n");
44    printf("      networkFile - network file for executing calibration
         run\n");
45    printf("      initialICF - file containing initial configuration;
         UNKNOWN marks intersections for analysis\n");
46    printf("      finalICF - file to output final intersection
         configuration\n");
47    printf("\n");
48    printf("Usage 2: To perform a run of a single node when a summary
         file is already available:\n");
49    printf("   warrant parametersFile nodeNumber outputFile\n");
50    printf("      parametersFile - standard parameters file, with
         summary file indicated\n");
51    printf("      nodeNumber - ID for the node to re-analyze");
52    printf("      outputFile - name for file to write the new control
         data");
53    exit(EXIT_FAILURE);
54 }
```

D.3 main_warrant.h

```
1  /*
2   Hierarchy of header files (bottom-up):
3
4   utils.h
5   datastructures.h
6   sampling.h
7   network.h
8   cell.h
9   vehicle.h
10  node.h
11  fileio.h
12  dta.h
13  warrant.h
14  main.h
15
16  Declarations referring to lower-level headers can use typedefs;
       declarations referring to higher-level headers must use structs
17 */
18
19
20 #include <stdlib.h>
21 #include "cell.h"
22 #include "dta.h"
23 #include "fileio.h"
24 #include "utils.h"
25 #include "warrant.h"
26
27 void displayUsage();
```

D.3.1 warrant.c

```
1  #include "warrant.h"
2
3  void generateBasicNodeControls(char *networkFileName, char *
      inputNodeControlFileName, char *outputNodeControlFileName) {
4     network_type *network = newScalar(network_type);
5     readNetworkFile(network, networkFileName, 1); /* Using dummy
         backward wave ratio; no simulation for the basic analysis.  (More
          sophisticated warrant analysis will change this.) */
6     createStarLists(network);
7    network->paths = createPathLinkedList();
8    readNodeControlFile(network, inputNodeControlFileName);
9     setAllNodesTo4WayStop(network);
10    writeNodeControlFile(network, outputNodeControlFileName);
```

```
11
12     /* Memory cleanup (only what's allocated in the functions called
          above */
13     deleteNetwork(network);
14 }
15
16 void generateWarrantNodeControls(char *parametersFileName, char *
       networkFileName, char *inputNodeControlFileName, char *
       outputNodeControlFileName) {
17   parameters_type trialRun;
18
19     /* Step 1: Generate temporary control file using basic controls */
20     generateBasicNodeControls(networkFileName, inputNodeControlFileName,
           TEMP_INTERSECTION_FILENAME);
21
22     /* Step 2: Create temporary parameters file: same as original
          parameters file but with temporary control file */
23     generateTemporaryParametersFile(parametersFileName,
          TEMP_INTERSECTION_FILENAME, TEMP_PARAMETERS_FILENAME);
24
25     /* Step 3: Perform a single run with temporary parameters file */
26     initializeDTARun(&trialRun, TEMP_PARAMETERS_FILENAME);
27     DTA(&trialRun);
28
29     /* Step 4: Do warrant analysis */
30     performWarrantAnalysis(&trialRun, inputNodeControlFileName);
31     writeNodeControlFile(trialRun.network, outputNodeControlFileName);
32
33     /* Step 5: Clean up by deleting temporary files */
34     if (remove(TEMP_INTERSECTION_FILENAME)) fatalError("Unable to delete
           temporary control file %s\n", TEMP_INTERSECTION_FILENAME);
35     if (remove(TEMP_PARAMETERS_FILENAME)) fatalError("Unable to delete
          temporary parameters file %s\n", TEMP_PARAMETERS_FILENAME);
36   cleanUpDTARun(&trialRun);
37 }
38
39 void generateTemporaryParametersFile(char *parametersFileName, char *
       newControlFileName, char *newParametersFileName) {
40     parameters_type tempRun;
41      readParametersFile(&tempRun, parametersFileName);
42     strncpy(tempRun.nodeControlFileName, newControlFileName, STRING_SIZE
          );
43     writeParametersFile(&tempRun, newParametersFileName);
44 }
45
46 void performWarrantAnalysis(parameters_type *run, char *
       originalControlFileName) {
```

```
47     int i;
48     network_type *network = run->network;
49     declareVector(bool, isUnknown, network->numNodes);
50
51     /* Read original node controls to see which nodes need a warrant
          analysis conducted */
52     scanControlFileForUnknown(originalControlFileName, isUnknown,
          network->numNodes);
53
54     /* First ensure that all centroids are properly labeled */
55     for (i = 0; i < network->numZones; i++) {
56        network->node[i].control = CENTROID;
57     }
58
59     /* Now process all other nodes */
60     for (; i < network->numNodes; i++) {
61        if (isUnknown[i] == TRUE) {
62           analyzeNode(run, i);
63        }
64     }
65
66     deleteVector(isUnknown);
67  }
68
69  /* i is the node to analyze */
70  void analyzeNode(parameters_type *run, int i) {
71     network_type *network = run->network;
72
73     arc_type *majorApproach1 = NULL, *majorApproach2 = NULL, *
          minorApproach = NULL;
74     /* First determine appropriate control type */
75     classifyApproaches(&(network->node[i]), network->timeHorizon, &
          majorApproach1, &majorApproach2, &minorApproach);
76     network->node[i].control = warrantedControl(&(network->node[i]),
          network->timeHorizon, run->timeHorizon, majorApproach1,
          majorApproach2, minorApproach);
77
78     /* Then perform any additional analysis needed for that control type
           */
79     switch (network->node[i].control) {
80     case NONHOMOGENEOUS:
81     case FOUR_WAY_STOP: /* Here no additional information is needed */
82        break;
83     case TWO_WAY_STOP: /* Here use angles to determine order of
          priorities */
84        createTwoWayStop(&(network->node[i]), majorApproach1,
             majorApproach2);
```

```
85          break;
86       case BASIC_SIGNAL: /* Put basic signal timing here */
87          createBasicSignal(&(network->node[i]), majorApproach1,
               majorApproach2, minorApproach, network->timeHorizon, run->
               timeHorizon);
88          break;
89       default:
90          fatalError("Unknown return value %d from warrantedControl!",
               network->node[i].control);
91       }
92    }
93
94
95    /*
96    Creates a "two-phase" signal.  Phase 1 is for majorApproach1 and
         majorApproach2.  Phase 2 is for minorApproach and everything else.
97     1. For major approach: X factor is max(v/c for major approach 1 and
          major approach 2)
98     2. For minor approach: X factor is v/c for minorApproach
99     3. Calculate cycle length: C = min(5/(1 - X_maj - X_min), MAX_LENGTH)
100    4. Then each phase's green time is proportionate X_maj / (X_maj + X-
          min) * C
101   This procedure IGNORES: clearance/lost time; saturation flow
         adjustments (including for turning); pedestrian crossing times
102   */
103   void createBasicSignal(node_type *node, arc_type *majorApproach1,
         arc_type *majorApproach2, arc_type *minorApproach, int timeSteps,
         float timeHorizon) {
104      int cycleLength, majorGreenTime, minorGreenTime;
105      float majorSaturation, minorSaturation;
106      double majorApproach1volume, majorApproach2volume,
            minorApproachVolume;
107      basicSignal_type *basicSignalControl;
108      arcLinkedListElt *upstreamArc, *downstreamArc;
109
110      displayMessage(DEBUG, "Creating basic signal for node %d\n", node->
            ID);
111
112      /* 1. If there are 2 approaches, make the second "major approach"
            the minor approach */
113      if (minorApproach == NULL) {
114         majorApproach2 = majorApproach1;
115         minorApproach = majorApproach2;
116      }
117
118      /* 2. Determine critical lane volumes, converting units as
            appropriate */
```

```
119     majorApproach1volume = majorApproach1->downstreamCount[timeSteps -
           1] / timeHorizon;
120     majorApproach2volume = majorApproach2->downstreamCount[timeSteps -
           1] / timeHorizon;
121     minorApproachVolume = minorApproach->downstreamCount[timeSteps - 1]
           / timeHorizon;
122     majorSaturation = max(majorApproach1volume / majorApproach1->
           capacity, majorApproach2volume / majorApproach2->capacity);
123     minorSaturation = minorApproachVolume / minorApproach->capacity;
124     displayMessage(DEBUG, "Major and minor saturation levels are %f and
           %f\n", majorSaturation, minorSaturation);
125
126     /* 3. Calculate cycle length using Webster's formula */
127     displayMessage(DEBUG, "Webster cycle length for this signal is %f\n"
           , 5.0 / (1 - majorSaturation - minorSaturation));
128     if (majorSaturation + minorSaturation > 1 - 5.0 / MAX_CYCLE_LENGTH)
           {
129        cycleLength = MAX_CYCLE_LENGTH;
130     } else {
131        cycleLength = max(MIN_CYCLE_LENGTH, rint(5 / (1 - majorSaturation
              - minorSaturation)));
132     }
133
134     /* 4. Allocate green times */
135     majorGreenTime = (majorSaturation / (majorSaturation +
           minorSaturation)) * cycleLength;
136     minorGreenTime = cycleLength - majorGreenTime;
137
138     /* 5. Set up signal data structure; note that green times are
           entered in the same order as in createAllPossibleMovements */
139     node->controlData = newScalar(basicSignal_type);
140     basicSignalControl = (basicSignal_type *)(node->controlData);
141     basicSignalControl->cycleLength = cycleLength;
142     basicSignalControl->greenTime = createLinkedList();
143     for (upstreamArc = node->reverseStar->head; upstreamArc != NULL;
           upstreamArc = upstreamArc->next) {
144        for (downstreamArc = node->forwardStar->head; downstreamArc !=
              NULL; downstreamArc = downstreamArc->next) {
145           if (downstreamArc->arc->head->ID == upstreamArc->arc->tail->ID
              ) continue; /* Skip U-turns */
146           if (upstreamArc->arc == majorApproach1 || upstreamArc->arc ==
              majorApproach2) {
147              insertLinkedList(basicSignalControl->greenTime,
                    majorGreenTime, NULL);
148           } else {
149              insertLinkedList(basicSignalControl->greenTime,
                    minorGreenTime, NULL);
```

```
150           }
151        }
152     }
153  }
154
155  /*
156  Two-way stop: tier 3.  tier 1 is a right turn or through from major;
        tier 2 is a let turn from major; tier 3 is anything else
157  */
158  void createTwoWayStop(node_type *node, arc_type *majorApproach1,
        arc_type *majorApproach2) {
159     float majorAngle1, majorAngle2, trialAngle;
160     priorityLinkedListElt *priority1, *priority2, *priority3;
161     twoWayStop_type *stopData;
162     turningLinkedListElt *curMovement;
163     arcLinkedListElt *upstreamArc, *downstreamArc;
164
165     /* 1. Determine angles */
166     majorAngle1 = atan2(majorApproach1->tail->Y - node->Y,
           majorApproach1->tail->X - node->X);
167     majorAngle2 = atan2(majorApproach2->tail->Y - node->Y,
           majorApproach2->tail->X - node->X);
168
169     /* 2. Set up stop data structure */
170     node->controlData = newScalar(twoWayStop_type);
171     stopData = (twoWayStop_type *)(node->controlData);
172    stopData->minStopPriority = 3;
173     stopData->priorityList = createPriorityLinkedList();
174     priority1 = insertPriorityLinkedList(stopData->priorityList, 1, NULL
           );
175     priority2 = insertPriorityLinkedList(stopData->priorityList, 2,
           priority1);
176     priority3 = insertPriorityLinkedList(stopData->priorityList, 3,
           priority2);
177     stopData->saturationFlow = majorApproach1->capacity;
178
179     /* 3. Assign each movement to an appropriate priority list:
180        major approach through/right = 1; major approach left = 2;
              everything else = 3
181        Cycles through list in the same order as movements are created in
               createAllPossibleMovements
182     */
183     curMovement = node->turnMovements->head;
184     for (upstreamArc = node->reverseStar->head; upstreamArc != NULL;
           upstreamArc = upstreamArc->next) {
185        for (downstreamArc = node->forwardStar->head; downstreamArc !=
              NULL; downstreamArc = downstreamArc->next) {
```

```
186          if (downstreamArc->arc->head->ID == upstreamArc->arc->tail->ID
                ) continue; /* Skip U-turns */
187          if (upstreamArc->arc == majorApproach1) {
188             trialAngle = atan2(downstreamArc->arc->head->Y - node->Y,
                   downstreamArc->arc->head->X - node->X);
189             if (majorAngle1 <= majorAngle2) {
190                if (majorAngle1 <= trialAngle && trialAngle <=
                      majorAngle2) { /* Right turn */
191                   insertTurningLinkedList(priority1->movements,
                         curMovement->movement, NULL);
192                } else {

                   /* Left turn */
193                   insertTurningLinkedList(priority2->movements,
                         curMovement->movement, NULL);
194                }
195             } else {
196                if (majorAngle2 <= trialAngle && trialAngle <=
                      majorAngle1) {  /* Left turn */
197                   insertTurningLinkedList(priority2->movements,
                         curMovement->movement, NULL);
198                } else {

                   /* Right turn */
199                   insertTurningLinkedList(priority1->movements,
                         curMovement->movement, NULL);
200                }
201             }
202          } else if (upstreamArc->arc == majorApproach2) {
203             trialAngle = atan2(downstreamArc->arc->head->Y - node->Y,
                   downstreamArc->arc->head->X - node->X);
204             if (majorAngle2 <= majorAngle1) {
205                if (majorAngle2 <= trialAngle && trialAngle <=
                      majorAngle1) { /* Right turn */
206                   insertTurningLinkedList(priority1->movements,
                         curMovement->movement, NULL);
207                } else {

                   /* Left turn */
208                   insertTurningLinkedList(priority2->movements,
                         curMovement->movement, NULL);
209                }
210             } else {
211                if (majorAngle1 <= trialAngle && trialAngle <=
                      majorAngle2) {  /* Left turn */
212                   insertTurningLinkedList(priority2->movements,
                         curMovement->movement, NULL);
```

```
213                 } else {

                       /* Right turn */
214                    insertTurningLinkedList(priority1->movements,
                          curMovement->movement, NULL);
215                 }
216              }
217           } else {
218              insertTurningLinkedList(priority3->movements, curMovement->
                    movement, NULL);
219           }
220           curMovement = curMovement->next;
221        }
222     }
223  }
224
225
226  void classifyApproaches (node_type *node, int timeSteps, arc_type **
        majorApproach1, arc_type **majorApproach2, arc_type **minorApproach)
         {
227     double majorApproach1volume, majorApproach2volume,
           minorApproachVolume, curVolume;
228     arcLinkedListElt *curArc;
229
230     /* Initialize search */
231     *majorApproach1 = NULL;
232     *majorApproach2 = NULL;
233     *minorApproach = NULL;
234     majorApproach1volume = -INFINITY;
235     majorApproach2volume = -INFINITY;
236     minorApproachVolume = -INFINITY;
237
238     for (curArc = node->reverseStar->head; curArc != NULL; curArc =
           curArc->next) {
239        curVolume = curArc->arc->downstreamCount[timeSteps - 1];
240        if (curVolume > majorApproach1volume) {
241           minorApproachVolume = majorApproach2volume;
242           majorApproach2volume = majorApproach1volume;
243           majorApproach1volume = curVolume;
244           *minorApproach = *majorApproach2;
245           *majorApproach2 = *majorApproach1;
246           *majorApproach1 = curArc->arc;
247        } else if (curVolume > majorApproach2volume) {
248           minorApproachVolume = majorApproach2volume;
249           majorApproach2volume = curVolume;
250           *minorApproach = *majorApproach2;
251           *majorApproach2 = curArc->arc;
```

```
252         } else if (curVolume > minorApproachVolume) {
253            minorApproachVolume = curVolume;
254            *minorApproach = curArc->arc;
255         }
256      }
257
258      /* Avoid compiler warning about parameter 'minorApproach' set but
            not used (the pointer is used by another function) */
259      if (*minorApproach == NULL) return;
260   }
261
262   /* Use volumes to classify approaches, and thereby determine
         appropriate control type */
263   intersection_type warrantedControl(node_type *node, int timeSteps,
         float timeHorizon, arc_type *majorApproach1, arc_type *
         majorApproach2, arc_type *minorApproach) {
264      int majorApproachLanes, minorApproachLanes;
265      double majorApproachVolume, minorApproachVolume, majorApproachFFS;
266
267      /* First handle easy cases */
268      if (node->reverseStar->size <= 0 || node->forwardStar->size <= 0) {
269         fatalError("Non-centroid node %d either has no approaches or no
               exits.", node->ID);
270      } else if (node->reverseStar->size == 1) {
271         if (node->forwardStar->size == 1) {
272            return NONHOMOGENEOUS;
273         } else {
274            return DIVERGE;
275         }
276      } else if (node->forwardStar->size == 1) {
277         return MERGE;
278      }
279
280      /* Need to add MERGE and DIVERGE as well */
281      if (majorApproach2 == NULL) return NONHOMOGENEOUS;
282
283      /* If there are 2 approaches, make the second "major approach" the
            minor approach */
284      if (minorApproach == NULL) {
285         majorApproachVolume = majorApproach1->downstreamCount[timeSteps -
               1];
286         minorApproachVolume = majorApproach2->downstreamCount[timeSteps -
               1];
287         majorApproachLanes = rint(majorApproach1->capacity / (
               BASE_SATURATION_FLOW / HOURS));
288         minorApproachLanes = rint(majorApproach2->capacity / (
               BASE_SATURATION_FLOW / HOURS));
```

```
289         majorApproachFFS = majorApproach1->length / majorApproach1->
                freeFlowTime;
290     } else { /* Usual case */
291         majorApproachVolume = max(majorApproach1->downstreamCount[
                timeSteps - 1], majorApproach2->downstreamCount[timeSteps -
                1]);
292         minorApproachVolume = minorApproach->downstreamCount[timeSteps -
                1];
293         majorApproachLanes = rint(max(majorApproach1->capacity,
                majorApproach2->capacity) / (BASE_SATURATION_FLOW / HOURS));
294         minorApproachLanes = rint(minorApproach->capacity / (
                BASE_SATURATION_FLOW / HOURS));
295         majorApproachFFS = max(majorApproach1->length / majorApproach1->
                freeFlowTime, majorApproach2->length/ majorApproach2->
                freeFlowTime);
296     }
297
298     /* Convert parameters to hourly units for MUTCD */
299     majorApproachVolume *= (HOURS / timeHorizon);
300     minorApproachVolume *= (HOURS / timeHorizon);
301     majorApproachFFS /= (MILES / HOURS);
302     displayMessage(DEBUG, "Major and minor approach volumes are %f and %
            f\n", majorApproachVolume, minorApproachVolume);
303
304     /* Now do warrant analysis based on volumes */
305     if (signalWarranted(majorApproachLanes, minorApproachLanes,
            majorApproachVolume, minorApproachVolume, majorApproachFFS) ==
            TRUE) return BASIC_SIGNAL;
306     if (fourWayStopWarranted(majorApproachVolume, minorApproachVolume)
            == TRUE) return FOUR_WAY_STOP;
307     if (twoWayStopWarranted(majorApproachVolume) == TRUE) return
            TWO_WAY_STOP;
308
309     return FOUR_WAY_STOP; /* Default control */
310 }
311
312 /* Based on MUTCD volume warrant  */
313 bool signalWarranted(int majorLanes, int minorLanes, double majorVolume
        , double minorVolume, double majorApproachFFS) {
314     if (minorLanes <= 1) {
315         if (majorLanes <= 1) {
316             if (majorVolume > 500 && minorVolume > 150) return TRUE;
317             if (majorVolume > 750 && minorVolume > 75) return TRUE;
318             if (majorVolume > 600 && minorVolume > 120) return TRUE;
319
320             if (majorApproachFFS <= 40) return FALSE;
321
```

```
322          if (majorVolume > 350 && minorVolume > 105) return TRUE;
323          if (majorVolume > 525 && minorVolume > 53) return TRUE;
324          if (majorVolume > 420 && minorVolume > 84) return TRUE;
325          return FALSE;
326       } else { /* More than one major lane */
327          if (majorVolume > 600 && minorVolume > 150) return TRUE;
328          if (majorVolume > 900 && minorVolume > 75) return TRUE;
329          if (majorVolume > 720 && minorVolume > 120) return TRUE;
330
331          if (majorApproachFFS <= 40) return FALSE;
332
333          if (majorVolume > 420 && minorVolume > 105) return TRUE;
334          if (majorVolume > 630 && minorVolume > 53) return TRUE;
335          if (majorVolume > 504 && minorVolume > 84) return TRUE;
336          return FALSE;
337       }
338    } else { /* More than one minor lane */
339       if (majorLanes <= 1) {
340          if (majorVolume > 500 && minorVolume > 200) return TRUE;
341          if (majorVolume > 750 && minorVolume > 100) return TRUE;
342          if (majorVolume > 600 && minorVolume > 160) return TRUE;
343
344          if (majorApproachFFS <= 40) return FALSE;
345
346          if (majorVolume > 350 && minorVolume > 140) return TRUE;
347          if (majorVolume > 525 && minorVolume > 70) return TRUE;
348          if (majorVolume > 420 && minorVolume > 112) return TRUE;
349          return FALSE;
350       } else { /* More than one major lane */
351          if (majorVolume > 600 && minorVolume > 200) return TRUE;
352          if (majorVolume > 900 && minorVolume > 100) return TRUE;
353          if (majorVolume > 720 && minorVolume > 160) return TRUE;
354
355          if (majorApproachFFS <= 40) return FALSE;
356
357          if (majorVolume > 420 && minorVolume > 140) return TRUE;
358          if (majorVolume > 630 && minorVolume > 70) return TRUE;
359          if (majorVolume > 504 && minorVolume > 112) return TRUE;
360          return FALSE;
361       }
362    }
363 }
364
365 bool fourWayStopWarranted(double majorVolume, double minorVolume) {
366    if (majorVolume > 300 && minorVolume > 200) {
367       return TRUE;
368    } else {
```

```
369         return FALSE;
370      }
371   }
372
373   bool twoWayStopWarranted(double majorVolume) {
374      if (majorVolume > 750) {
375         return TRUE;
376      } else {
377         return FALSE;
378      }
379   }
380
381   void setAllNodesTo4WayStop(network_type *network) {
382      int i;
383
384      /* Take care of centroids... */
385      for (i = 0; i < network->numZones; i++) {
386         network->node[i].control = CENTROID;
387      }
388
389      /* Then generate all other possible movements, without creating U-
            turns */
390      for (; i < network->numNodes; i++) {
391         if (network->node[i].control != UNKNOWN_CONTROL) continue; /* Don
               't disturb known intersections */
392         network->node[i].control = FOUR_WAY_STOP;
393         createAllPossibleMovements(&(network->node[i]));
394      }
395
396   }
397
398   void createAllPossibleMovements(node_type *node) {
399      arcLinkedListElt *upstreamArc, *downstreamArc;
400      turning_type *newMovement;
401
402      for (upstreamArc = node->reverseStar->head; upstreamArc != NULL;
            upstreamArc = upstreamArc->next) {
403         for (downstreamArc = node->forwardStar->head; downstreamArc !=
               NULL; downstreamArc = downstreamArc->next) {
404            if (downstreamArc->arc->head->ID == upstreamArc->arc->tail->ID
                  ) continue; /* Skip U-turns */
405            newMovement = newScalar(turning_type);
406            createMovement(newMovement, upstreamArc->arc->tail->ID, node->
                  ID, downstreamArc->arc->head->ID, node);
407            newMovement->saturationFlow = upstreamArc->arc->capacity;
408         }
409      }
```

```
410 }
411
412 void scanControlFileForUnknown(char *controlFileName, bool *isUnknown,
       int numNodes) {
413    int i, status;
414    char fullLine[STRING_SIZE], trimmedLine[STRING_SIZE], controlText[
          STRING_SIZE];
415    FILE *controlFile = openFile(controlFileName, "r");
416
417    while (!feof(controlFile)) {
418     if (fgets(fullLine, STRING_SIZE, controlFile) == NULL) break;
419     status = parseLine(fullLine, trimmedLine);
420     if (status == BLANK_LINE || status == COMMENT) continue;
421     if (strncmp(trimmedLine, "Node", 4) == 0) {
422       sscanf(trimmedLine, "Node %d : %s", &i, controlText);
423       }
424     if (i < 1 || i > numNodes) {
425          warning(FULL_NOTIFICATIONS, "Node out of range in control file
                .  Ignoring input line:\n%s\n", fullLine);
426          continue;
427     }
428     if (strcmp(controlText, "UNKNOWN") == 0) {
429          isUnknown[i-1] = TRUE;
430       } else {
431          isUnknown[i-1] = FALSE;
432       }
433    }
434    fclose(controlFile);
435 }
```

D.3.2 warrant.h

```
1  #ifndef _WARRANT_H_
2  #define _WARRANT_H_
3
4  #include "dta.h"
5  #include "fileio.h"
6  #include "network.h"
7  #include "datastructures.h"
8  #include "utils.h"
9  #include <math.h>
10
11 #define BASE_SATURATION_FLOW 1900
12
13 #define MIN_CYCLE_LENGTH 20
14 #define MAX_CYCLE_LENGTH 120
15
```

```
16 #define TEMP_INTERSECTION_FILENAME "~TEMP.ICF"
17 #define TEMP_PARAMETERS_FILENAME "~TEMP_PARAMETERS.TXT"
18
19 void generateBasicNodeControls(char *networkFileName, char *
      inputNodeControlFileName, char *outputNodeControlFileName);
20 void generateWarrantNodeControls(char *parametersFileName, char *
      networkFileName, char *inputNodeControlFileName, char *
      outputNodeControlFileName);
21 void generateTemporaryParametersFile(char *parametersFileName, char *
      newControlFileName, char *newParametersFileName);
22
23 void classifyApproaches (node_type *node, int timeSteps, arc_type **
      majorApproach1, arc_type **majorApproach2, arc_type **minorApproach)
      ;
24 void performWarrantAnalysis(parameters_type *run, char *
      originalControlFileName);
25 intersection_type warrantedControl(node_type *node, int timeSteps,
      float timeHorizon, arc_type *majorApproach1, arc_type *
      majorApproach2, arc_type *minorApproach);
26
27 bool signalWarranted(int majorLanes, int minorLanes, double majorVolume
      , double minorVolume, double majorApproachFFS);
28 bool fourWayStopWarranted(double majorVolume, double minorVolume);
29 bool twoWayStopWarranted(double majorVolume);
30
31 void createBasicSignal(node_type *node, arc_type *majorApproach1,
      arc_type *majorApproach2, arc_type *minorApproach, int timeSteps,
      float timeHorizon);
32 void createTwoWayStop(node_type *node, arc_type *majorApproach1,
      arc_type *majorApproach2);
33
34 void setAllNodesTo4WayStop(network_type *network);
35 void createAllPossibleMovements(node_type *node);
36 void scanControlFileForUnknown(char *controlFileName, bool *isUnknown,
      int numNodes);
37
38 void analyzeNode(parameters_type *run, int i);
39 #endif
```

D.4 Graphics module

D.4.1 main_graphics.c

```
1 #include "main_graphics.h"
2
```

```
3  /* Primary main file for running simulation.  Uncomment #if 0 and #
       endif to compile this one. */
4  int main(int numArgs, char *args[]) {
5
6
7    parameters_type run;
8     graphicsParameters_type graphicsParameters;
9
10    /* int t; */
11    verbosity = FULL_NOTIFICATIONS;
12
13    #ifdef DEBUG_MODE /* Debug mode enables extra logging.  Define this
          macro in utils.h */
14       debugFile = openFile("logfile.txt", "w");
15       /* verbosity = FULL_DEBUG; */
16       displayMessage(DEBUG, "Starting new run.\n");
17    #endif
18
19    if (numArgs != 2) displayUsage();
20
21   initializeDTARun(&run, args[1]);
22    initializeGraphics(&graphicsParameters, &run);
23    readCumulativeCounts(run.network, run.countsFileName);
24
25    if (graphicsParameters.snapshotMode == TRUE) {
26       for (t = 0; t < run.network->timeHorizon; t++) {
27          generateBitmap(&graphicsParameters, run.network, t);
28       }
29    } else {
30       generateFinalBitmap(&graphicsParameters, &run);
31    }
32
33   cleanUpDTARun(&run);
34    cleanUpGraphics(&graphicsParameters);
35
36    #ifdef DEBUG_MODE
37       fclose(debugFile);
38    #endif
39
40   return (EXIT_SUCCESS);
41 }
42
43 void displayUsage() {
44    fatalError("Program requires exactly one argument - run parameters
          file.");
45 }
```

D.5 main_graphics.h

```
1  /*
2   Hierarchy of header files (bottom-up):
3
4   utils.h
5   datastructures.h
6   sampling.h
7   network.h
8   cell.h
9   vehicle.h
10  node.h
11  fileio.h
12  dta.h
13  main.h
14
15  Declarations referring to lower-level headers can use typedefs;
       declarations referring to higher-level headers must use structs
16 */
17
18
19 #include <stdlib.h>
20 #include "cell.h"
21 #include "fileio.h"
22 #include "utils.h"
23 #include "graphics.h"
24 #include "warrant.h"
25
26 void displayUsage();
```

D.5.1 graphics.c

```
1  #include "graphics.h"
2  #include "characters.h"
3
4  /*******************************
5   ** Image conversion routines **
6   *******************************/
7
8  void absolute2relative(graphicsParameters_type *graphicsParameters,
      float absoluteX, float absoluteY, int *relativeX, int *relativeY,
      int minX, int minY) {
9    *relativeX = graphicsParameters->borderWidth + graphicsParameters->
       imageWidth  * ((absoluteX - minX) / graphicsParameters->
       absoluteXrange);
10   *relativeY = graphicsParameters->borderWidth + graphicsParameters->
```

```
        imageHeight * (1 - (absoluteY - minY) / graphicsParameters->
        absoluteYrange);
11
12  }
13
14  int density2red(int density, int jamDensity) {
15    return density * 255 / jamDensity;
16  }
17
18  int density2green(int density, int jamDensity) {
19    return (jamDensity - density) * 255 / jamDensity;
20  }
21
22  int density2blue(int density, int jamDensity) {
23    return (density > 0) ? 0 : 128;
24    return 0;
25    return 0 * (density + jamDensity); /* Never reached, but silences
         compiler warnings about unused arguments. */
26  }
27
28  #if 0
29  void generateFinalNodeBitmap(graphicsParameters_type *
       graphicsParameters, parameters_type *run, node_type *node) {
30      int i, ij;
31      char filename[STRING_SIZE];
32      network_type *network = run->network;
33      bitmap_type bitmap;
34
35      displayMessage(FULL_NOTIFICATIONS, "Writing image file ");
36      bitmap.height = graphicsParameters->imageHeight + 2 *
           graphicsParameters->borderWidth;
37      bitmap.width = graphicsParameters->imageWidth + 2 *
           graphicsParameters->borderWidth;
38      bitmap.pixels = newVector(bitmap.height * bitmap.width, pixel_type);
39      resetBitmap(&bitmap, 0, 0, 0);
40
41      /* Draw arcs adjacent only to a single node */
42      for (ij = 0; ij < network->numArcs; ij++) {
43          if (network->arc[ij].head == node ) {
44              drawOverallArc(&bitmap, graphicsParameters, ij, run);
45              drawNode(&bitmap, graphicsParameters, ptr2node(network->arc[ij
                   ].tail));
46          }
47          if (network->arc[ij].tail == node) {
48              drawOverallArc(&bitmap, graphicsParameters, ij, run);
49              drawNode(&bitmap, graphicsParameters, ptr2node(network->arc[ij
                   ].head));
```

```
50        }
51     }
52
53     /* Write file */
54     sprintf(filename, "%s_node%d.png", graphicsParameters->graphicsRoot,
           node->ID);
55     writePNG(&bitmap, filename);
56     deleteVector(bitmap.pixels);
57     displayMessage(FULL_NOTIFICATIONS, "%s complete.\n", filename);
58  }
59  #endif
60
61  #define PLACEHOLDER_TIME 0
62  void generateFinalBitmap(graphicsParameters_type *graphicsParameters,
       parameters_type *run) {
63     int i, ij, t;
64     int oldUpstream, oldDownstream;
65     int upstream, downstream;
66     char filename[STRING_SIZE];
67     int startTime = run->warmUpLength / run->tickLength, endTime = (run
          ->timeHorizon - run->coolDownLength) / run->tickLength;
68    int numPeriods = endTime - startTime;
69    network_type *network = run->network;
70     bitmap_type bitmap;
71
72
73     displayMessage(FULL_NOTIFICATIONS, "Writing image file ");
74    if (numPeriods < 1) {
75       warning(LOW_NOTIFICATIONS, "Can't generate final bitmap file,
             entire run is warm-up or cool-down.\n");
76       return;
77    }
78
79     bitmap.height = graphicsParameters->imageHeight + 2 *
          graphicsParameters->borderWidth;
80     bitmap.width = graphicsParameters->imageWidth + 2 *
          graphicsParameters->borderWidth;
81     bitmap.pixels = newVector(bitmap.height * bitmap.width, pixel_type);
82     resetBitmap(&bitmap, 0, 0, 0);
83
84
85     /* Draw arcs */
86     for (ij = 0; ij < network->numArcs; ij++) {
87        oldUpstream = network->arc[ij].upstreamCount[PLACEHOLDER_TIME];
88        oldDownstream = network->arc[ij].downstreamCount[PLACEHOLDER_TIME
             ];
89        upstream = 0; downstream = 0;
```

```
90          for (t = startTime; t < endTime; t++) {
91             upstream += network->arc[ij].upstreamCount[t];
92             downstream += network->arc[ij].downstreamCount[t];
93          }
94          network->arc[ij].upstreamCount[PLACEHOLDER_TIME] = upstream /
               numPeriods;
95          network->arc[ij].downstreamCount[PLACEHOLDER_TIME] = downstream /
                numPeriods;
96          drawArc(&bitmap, graphicsParameters, ij, network,
               PLACEHOLDER_TIME);
97          network->arc[ij].upstreamCount[PLACEHOLDER_TIME] = oldUpstream;
98          network->arc[ij].downstreamCount[PLACEHOLDER_TIME] =
               oldDownstream;
99       }
100
101      /* Draw nodes */
102       for (i = network->numZones; i < network->numNodes; i++) {
103          drawNode(&bitmap, graphicsParameters, i);
104       }
105
106       /* Write file */
107       sprintf(filename, "%s_final.png", graphicsParameters->graphicsRoot);
108       writePNG(&bitmap, filename);
109       deleteVector(bitmap.pixels);
110       displayMessage(FULL_NOTIFICATIONS, "%s complete.\n", filename);
111    }
112
113    void generateBitmap(graphicsParameters_type *graphicsParameters,
          network_type *network, int t) {
114       int i, ij, numDigits = ceil(log10(network->timeHorizon));
115       char filename[STRING_SIZE], formatString[STRING_SIZE];
116       bitmap_type bitmap;
117
118       displayMessage(FULL_NOTIFICATIONS, "Writing image file ");
119       bitmap.height = graphicsParameters->imageHeight + 2 *
             graphicsParameters->borderWidth;
120       bitmap.width = graphicsParameters->imageWidth + 2 *
             graphicsParameters->borderWidth;
121       bitmap.pixels = newVector(bitmap.height * bitmap.width, pixel_type);
122       resetBitmap(&bitmap, 127, 127, 127);
123
124       /* Draw arcs */
125       for (ij = 0; ij < network->numArcs; ij++) {
126          if (network->arc[ij].head->controlType != CENTROID && network->
               arc[ij].tail->controlType != CENTROID)
127             drawArc(&bitmap, graphicsParameters, ij, network, t);
128       }
```

```
129
130   /* Draw nodes */
131    for (i = network->numZones; i < network->numNodes; i++) {
132       drawNode(&bitmap, graphicsParameters, i);
133    }
134
135    /* Write file */
136    sprintf(formatString, "%%s%%0%dd.png", numDigits);
137    sprintf(filename, formatString, graphicsParameters->graphicsRoot, t)
          ;
138    writePNG(&bitmap, filename);
139    deleteVector(bitmap.pixels);
140    displayMessage(FULL_NOTIFICATIONS, "%s complete.\n", filename);
141 }
142
143 /***** Drawing routines *****/
144
145 void drawArc(bitmap_type *bitmap, graphicsParameters_type *
       graphicsParameters, int ij, network_type *network, int t) {
146    int x, y, baseX, baseY;
147    int tail = ptr2node(network, network->arc[ij].tail);
148    int head = ptr2node(network, network->arc[ij].head);
149    int red, green, blue;
150    int numVehicles = network->arc[ij].upstreamCount[t] - network->arc[
          ij].downstreamCount[t];
151    int maxVehicles = network->arc[ij].jamDensity * network->arc[ij].
          length;
152
153    displayMessage(DEBUG, "Drawing arc (%d,%d)\n", network->arc[ij].tail
          ->ID, network->arc[ij].head->ID);
154    /* Identify colors */
155    if (maxVehicles == 0) { /* Shade white for links with no allowable
          vehicles */
156       red = 127;
157       green = 127;
158       blue = 127;
159    } else {
160       red = density2red(numVehicles, maxVehicles);
161       green = density2green(numVehicles, maxVehicles);
162       blue = density2blue(numVehicles, maxVehicles);
163    }
164
165    switch(graphicsParameters->arcSlope[ij]) {
166    case SHALLOW: /* Iterate over x direction, finding appropriate y.
          arcRelativeDX must be nonzero */
167       if (graphicsParameters->arcRelativeDX[ij] > 0) { /* Arc moves
             from left-to-right, draw on bottom */
```

```
168           for (x = BOTTOM_RIGHT_X(tail); x <= BOTTOM_LEFT_X(head); x++)
                 {
169              if (BOTTOM_LEFT_X(head) == BOTTOM_RIGHT_X(tail)) continue;
170              baseY = BOTTOM_RIGHT_Y(tail) + (x - BOTTOM_RIGHT_X(tail)) *
                     (BOTTOM_LEFT_Y(head) - BOTTOM_RIGHT_Y(tail)) / (
                    BOTTOM_LEFT_X(head) - BOTTOM_RIGHT_X(tail));
171              for (y = baseY; y >= baseY - graphicsParameters->linkWidth;
                     y--) {
172                 setPixel(bitmap, x, y, red, green, blue);
173              }
174           }
175        } else { /* Arc moves from right-to-left, draw on top */
176           for (x = TOP_LEFT_X(tail); x >= TOP_RIGHT_X(head); x--) {
177              if (TOP_RIGHT_X(head) == TOP_LEFT_X(tail)) continue;
178              baseY = TOP_LEFT_Y(tail) + (x - TOP_LEFT_X(tail)) * (
                    TOP_RIGHT_Y(head) - TOP_LEFT_Y(tail)) / (TOP_RIGHT_X(
                    head) - TOP_LEFT_X(tail));
179              for (y = baseY; y <= baseY + graphicsParameters->linkWidth;
                     y++) {
180                 setPixel(bitmap, x, y, red, green, blue);
181              }
182           }
183        }
184        break;
185     case STEEP: /* Iterative over y direction, finding appropriate x.
           arcRelativeDY must be nonzero */
186        if (graphicsParameters->arcRelativeDY[ij] < 0) { /* Arc moves
           from bottom-to-top, draw on right */
187           for (y = TOP_RIGHT_Y(tail); y >= BOTTOM_RIGHT_Y(head); y--) {
188              if (BOTTOM_RIGHT_Y(head) == TOP_RIGHT_Y(tail)) continue;
189              baseX = TOP_RIGHT_X(tail) + (y - TOP_RIGHT_Y(tail)) * (
                    BOTTOM_RIGHT_X(head) - TOP_RIGHT_X(tail)) / (
                    BOTTOM_RIGHT_Y(head) - TOP_RIGHT_Y(tail));
190              for (x = baseX; x >= baseX - graphicsParameters->linkWidth;
                     x--) {
191                 setPixel(bitmap, x, y, red, green, blue);
192              }
193           }
194        } else { /* Arc moves from top-to-bottom, draw on left */
195           for (y = BOTTOM_LEFT_Y(tail); y <= TOP_LEFT_Y(head); y++) {
196              if (TOP_LEFT_Y(head) == BOTTOM_LEFT_Y(tail)) continue;
197              baseX = BOTTOM_LEFT_X(tail) + (y - BOTTOM_LEFT_Y(tail)) * (
                    TOP_LEFT_X(head) - BOTTOM_LEFT_X(tail)) / (TOP_LEFT_Y(
                    head) - BOTTOM_LEFT_Y(tail));
198              for (x = baseX; x <= baseX + graphicsParameters->linkWidth;
                     x++) {
199                 setPixel(bitmap, x, y, red, green, blue);
```

```
200             }
201          }
202       }
203       break;
204    default:
205       fatalError("Unknown arc slope!");
206    }
207 }
208
209 void drawNode(bitmap_type *bitmap, graphicsParameters_type *
      graphicsParameters, int i) {
210    int x, y, nodeRadius = graphicsParameters->nodeRadius;
211    for (x = graphicsParameters->relativeNodeX[i] - nodeRadius; x <=
         graphicsParameters->relativeNodeX[i] + nodeRadius; x++) {
212       for (y = graphicsParameters->relativeNodeY[i] - nodeRadius; y <=
            graphicsParameters->relativeNodeY[i] + nodeRadius; y++) {
213          setPixel(bitmap, x, y, 255, 255, 255);
214       }
215    }
216    plopLabel(bitmap, i+1, BOTTOM_LEFT_X(i), BOTTOM_LEFT_Y(i) +
         graphicsParameters->nodeRadius, 255, 0, 0);
217 }
218
219 void plopLabel(bitmap_type *bitmap, long label, int upperLeftX, int
      upperLeftY, int red, int green, int blue) {
220    int ptr = 0, digit;
221    int x = upperLeftX;
222    char buffer[STRING_SIZE];
223    sprintf(buffer, "%ld", label);
224    while (buffer[ptr] != '\0') {
225       digit = buffer[ptr] - '0'; /* Assumes character encoding has
            numbers sequentially after 0 */
226       plopDigit(bitmap, digit, x, upperLeftY, red, green, blue);
227       x += CHAR_WIDTH + 1;
228       ptr++;
229    }
230 }
231
232 void plopDigit(bitmap_type *bitmap, int digit, int upperLeftX, int
      upperLeftY, int red, int green, int blue) {
233    int x, y;
234    for (x = 0; x < CHAR_WIDTH; x++) {
235       for (y = 0; y < CHAR_HEIGHT; y++) {
236          if (digitFont[digit][y][x] != 0) setPixel(bitmap, x +
               upperLeftX, y + upperLeftY, red, green, blue);
237       }
238    }
```

```
239 }
240
241 void resetBitmap(bitmap_type *bitmap, unsigned char red, unsigned char
       green, unsigned char blue) {
242   int x, y;
243   for (y = 0; y < bitmap->height; y++) {
244     for (x = 0; x < bitmap->width; x++) {
245       setPixel(bitmap, x, y, red, green, blue);
246     }
247   }
248 }
249
250 void setPixel(bitmap_type *bitmap, int x, int y, unsigned char red,
       unsigned char green, unsigned char blue) {
251   pixel_type *pixel = coord2pixel(bitmap, x, y);
252   if (x < 0 || x >= bitmap->width || y < 0 || y >= bitmap->height)
        return;
253
254   pixel->red = red;
255   pixel->green = green;
256   pixel->blue = blue;
257 }
258
259 /***** Handle graphics data structures *****/
260
261 void cleanUpGraphics(graphicsParameters_type *graphicsParameters) {
262   deleteVector(graphicsParameters->relativeNodeX);
263   deleteVector(graphicsParameters->relativeNodeY);
264   deleteVector(graphicsParameters->arcRelativeDX);
265   deleteVector(graphicsParameters->arcRelativeDY);
266   deleteVector(graphicsParameters->arcSlope);
267 }
268
269 void initializeGraphics(graphicsParameters_type *graphicsParameters,
       parameters_type *run) {
270   int i, ij;
271   float minX = INFINITY, maxX = -INFINITY, minY = INFINITY, maxY = -
        INFINITY;
272    network_type *network = run->network;
273
274    if (strlen(run->graphicsFileName) == 0) fatalError("Missing graphics
         parameter file!");
275    readGraphicsParametersFile(graphicsParameters, run->graphicsFileName
        );
276
277   graphicsParameters->relativeNodeX = newVector(network->numNodes, int)
        ;
```

```
278   graphicsParameters->relativeNodeY = newVector(network->numNodes, int)
         ;
279   graphicsParameters->arcRelativeDX = newVector(network->numArcs, int);
280   graphicsParameters->arcRelativeDY = newVector(network->numArcs, int);
281   graphicsParameters->arcSlope = newVector(network->numArcs, slope_type
         );
282
283   for (i = 0; i < network->numNodes; i++) {
284     minX = min(minX, network->node[i].X);
285     maxX = max(maxX, network->node[i].X);
286     minY = min(minY, network->node[i].Y);
287     maxY = max(maxY, network->node[i].Y);
288   }
289   graphicsParameters->absoluteXrange = maxX - minX + 1; /* Add one to
         ensure absolute ranges are at least 1 */
290   graphicsParameters->absoluteYrange = maxY - minY + 1;
291
292   for (i = 0; i < network->numNodes; i++) {
293      absolute2relative(graphicsParameters, network->node[i].X, network
         ->node[i].Y, &(graphicsParameters->relativeNodeX[i]), &(
         graphicsParameters->relativeNodeY[i]), minX, minY);
294   }
295
296   for (ij = 0; ij < network->numArcs; ij++) {
297      graphicsParameters->arcRelativeDX[ij] = graphicsParameters->
         relativeNodeX[network->arc[ij].head->ID-1] - graphicsParameters
         ->relativeNodeX[network->arc[ij].tail->ID-1];
298      graphicsParameters->arcRelativeDY[ij] = graphicsParameters->
         relativeNodeY[network->arc[ij].head->ID-1] - graphicsParameters
         ->relativeNodeY[network->arc[ij].tail->ID-1];
299      if (abs(graphicsParameters->arcRelativeDX[ij]) > abs(
         graphicsParameters->arcRelativeDY[ij]))
300          graphicsParameters->arcSlope[ij] = SHALLOW;
301       else
302          graphicsParameters->arcSlope[ij] = STEEP;
303   }
304
305 }
306
307 void readGraphicsParametersFile(graphicsParameters_type *
       graphicsParameters, char *graphicsParametersFileName) {
308   int status;
309   char fullLine[STRING_SIZE];
310   char metadataTag[STRING_SIZE], metadataValue[STRING_SIZE];
311   FILE *graphicsParametersFile = openFile(graphicsParametersFileName, "
         r");
312
```

```
313   /* Set default parameter values */
314   graphicsParameters->imageWidth = 500;
315   graphicsParameters->imageHeight = 500;
316   graphicsParameters->borderWidth = 50;
317   graphicsParameters->nodeRadius = 5;
318   graphicsParameters->linkWidth = 2;
319   graphicsParameters->graphicsRoot[0] = '\0';
320   graphicsParameters->snapshotMode = FALSE;
321
322   /* Process parameter file */
323   while (!feof(graphicsParametersFile)) {
324     do {
325       if (fgets(fullLine, STRING_SIZE, graphicsParametersFile) == NULL)
              break;
326       status = parseMetadata(fullLine, metadataTag, metadataValue);
327     } while (status == BLANK_LINE || status == COMMENT);
328     if        (strcmp(metadataTag, "IMAGE WIDTH") == 0) {
329       graphicsParameters->imageWidth = atoi(metadataValue);
330     } else if (strcmp(metadataTag, "IMAGE HEIGHT") == 0) {
331       graphicsParameters->imageHeight = atoi(metadataValue);
332     } else if (strcmp(metadataTag, "BORDER WIDTH") == 0) {
333       graphicsParameters->borderWidth = atoi(metadataValue);
334     } else if (strcmp(metadataTag, "NODE RADIUS") == 0) {
335       graphicsParameters->nodeRadius = atoi(metadataValue);
336     } else if (strcmp(metadataTag, "LINK WIDTH") == 0) {
337       graphicsParameters->linkWidth = atoi(metadataValue);
338     } else if (strcmp(metadataTag, "PNG ROOT") == 0) {
339       strcpy(graphicsParameters->graphicsRoot, metadataValue);
340     } else if (strcmp(metadataTag, "SNAPSHOTS") == 0) {
341       graphicsParameters->snapshotMode = TRUE;
342     } else {
343       warning(MEDIUM_NOTIFICATIONS, "Ignoring unknown metadata tag in
             parameters file - %s\n", metadataTag);
344     }
345   }
346
347   /* Check mandatory elements are present and validate input */
348   if (graphicsParameters->imageWidth <= 0) fatalError("Image width must
        be positive!");
349   if (graphicsParameters->imageHeight <= 0) fatalError("Image height
       must be positive!");
350   if (graphicsParameters->borderWidth < 0) fatalError("Border width
       must be nonnegative!");
351   if (graphicsParameters->nodeRadius <= 0) fatalError("Node radius must
        be positive!");
352   if (graphicsParameters->linkWidth <= 0) fatalError("Link width must
       be positive!");
```

```
353   if (strlen(graphicsParameters->graphicsRoot) == 0) warning(
          FULL_NOTIFICATIONS, "Graphics root is empty.");
354
355   fclose(graphicsParametersFile);
356   displayMessage(DEBUG, "Finished reading graphics parameters file.\n")
          ;
357
358 }
359
360
361 /*************************
362  ** PNG writing routines **
363  *************************/
364
365 pixel_type *coord2pixel(bitmap_type *bitmap, int x, int y) {
366   return bitmap->pixels + bitmap->width * y + x;
367 }
368
369 void writePNG(bitmap_type *bitmap, char *pngFilename) {
370   int x, y;
371   png_byte *row, **rowPtr = NULL;
372   pixel_type *pixel;
373   FILE *pngFile = openFile(pngFilename, "wb");
374   png_structp png = png_create_write_struct(PNG_LIBPNG_VER_STRING, NULL
          , NULL, NULL);
375   png_infop info = png_create_info_struct(png);
376
377   if (png == NULL || info == NULL) fatalError("Error allocating memory
          for PNG structures!");
378   if (setjmp(png_jmpbuf(png))) fatalError("Error writing PNG file!");
379
380   png_set_IHDR (png, info, bitmap->width, bitmap->height, DEPTH,
          PNG_COLOR_TYPE_RGB, PNG_INTERLACE_NONE,
          PNG_COMPRESSION_TYPE_DEFAULT, PNG_FILTER_TYPE_DEFAULT);
381
382   rowPtr = png_malloc(png, bitmap->height * sizeof(png_byte *));
383   for (y = 0; y < bitmap->height; y++) {
384     row = png_malloc(png, sizeof(unsigned char) * bitmap->width *
            PIXEL_SIZE);
385     rowPtr[y] = row;
386     for (x = 0; x < bitmap->width; x++) {
387       pixel = coord2pixel(bitmap, x, y);
388       *row++ = pixel->red;
389       *row++ = pixel->green;
390       *row++ = pixel->blue;
391     }
392   }
```

```
393
394   png_init_io(png, pngFile);
395   png_set_rows(png, info, rowPtr);
396   png_write_png(png, info, PNG_TRANSFORM_IDENTITY, NULL);
397
398   for (y = 0; y < bitmap->height; y++) {
399     png_free(png, rowPtr[y]);
400   }
401   png_free(png, rowPtr);
402   png_destroy_write_struct (&png, &info);
403   fclose(pngFile);
404 }
```

D.5.2 graphics.h

```
1  #ifndef _GRAPHICS_H_
2  #define _GRAPHICS_H_
3
4  #include <math.h>
5  #include <png.h>
6  #include <zlib.h>
7  #include "network.h"
8  #include "utils.h"
9
10 #define PIXEL_SIZE 3
11 #define DEPTH 8
12
13 /* Relative coordinate points for a node i.  To use these,
      graphicsParameters must be a pointer to the relevant graphics struct
       */
14 #define TOP_RIGHT_X(i)    (graphicsParameters->relativeNodeX[i] +
      graphicsParameters->nodeRadius)
15 #define TOP_RIGHT_Y(i)    (graphicsParameters->relativeNodeY[i] -
      graphicsParameters->nodeRadius)
16 #define TOP_LEFT_X(i)     (graphicsParameters->relativeNodeX[i] -
      graphicsParameters->nodeRadius)
17 #define TOP_LEFT_Y(i)     (graphicsParameters->relativeNodeY[i] -
      graphicsParameters->nodeRadius)
18 #define BOTTOM_RIGHT_X(i) (graphicsParameters->relativeNodeX[i] +
      graphicsParameters->nodeRadius)
19 #define BOTTOM_RIGHT_Y(i) (graphicsParameters->relativeNodeY[i] +
      graphicsParameters->nodeRadius)
20 #define BOTTOM_LEFT_X(i)  (graphicsParameters->relativeNodeX[i] -
      graphicsParameters->nodeRadius)
21 #define BOTTOM_LEFT_Y(i)  (graphicsParameters->relativeNodeY[i] +
      graphicsParameters->nodeRadius)
22
```

```
23 typedef enum {
24   SHALLOW,
25   STEEP
26 } slope_type;
27
28 typedef struct graphicsParameters_s {
29   int imageWidth; /* Image width and height *excludes* border */
30   int imageHeight;
31   int borderWidth;
32   int nodeRadius;
33   int linkWidth;
34   int *relativeNodeX; /* Arrays containing node X and Y coordinates in
        relative coordinates */
35   int *relativeNodeY; /* Note relative Y direction is reversed...
        positive downwards, while absolute Y is positive upwards */
36   int *arcRelativeDX;
37   int *arcRelativeDY;
38   slope_type *arcSlope;
39   char graphicsRoot[STRING_SIZE];
40   char graphicsParametersFilename[STRING_SIZE];
41   float absoluteXrange;
42   float absoluteYrange;
43   bool  snapshotMode;
44 } graphicsParameters_type;
45
46 typedef struct {
47   unsigned char red;
48   unsigned char green;
49   unsigned char blue;
50 } pixel_type;
51
52 typedef struct {
53   pixel_type *pixels;
54   int width;
55   int height;
56 } bitmap_type;
57
58 #include "fileio.h" /* Dependencies require this to be included after
      declaration of graphicsParameters_type */
59
60
61 /***** Image conversion routines *****/
62
63 void absolute2relative(graphicsParameters_type *graphicsParameters,
      float absoluteX, float absoluteY, int *relativeX, int *relativeY,
      int minX, int minY);
64 int density2red(int density, int jamDensity);
```

```
65 int density2green(int density, int jamDensity);
66 int density2blue(int density, int jamDensity);
67 void generateBitmap(graphicsParameters_type *graphicsParameters,
      network_type *network, int t);
68 void generateFinalBitmap(graphicsParameters_type *graphicsParameters,
      parameters_type *run);
69
70 /***** Drawing routines *****/
71
72 void drawArc(bitmap_type *bitmap, graphicsParameters_type *
      graphicsParameters, int ij, network_type *network, int t);
73 void drawNode(bitmap_type *bitmap, graphicsParameters_type *
      graphicsParameters, int i);
74 void plopLabel(bitmap_type *bitmap, long label, int upperLeftX, int
      upperLeftY, int red, int green, int blue);
75 void plopDigit(bitmap_type *bitmap, int digit, int upperLeftX, int
      upperLeftY, int red, int green, int blue);
76 void resetBitmap(bitmap_type *bitmap, unsigned char red, unsigned char,
       unsigned char blue);
77 void setPixel(bitmap_type *bitmap, int x, int y, unsigned char red,
      unsigned char green, unsigned char blue);
78
79 /***** Handle graphics data structures *****/
80
81 void cleanUpGraphics(graphicsParameters_type *graphicsParameters);
82 void initializeGraphics(graphicsParameters_type *graphicsParameters,
      parameters_type *run);
83 void readGraphicsParametersFile(graphicsParameters_type *
      graphicsParameters, char *graphicsParametersFileName);
84
85 /***** PNG manipulation routines *****/
86
87 pixel_type *coord2pixel(bitmap_type *bitmap, int x, int y);
88 void writePNG(bitmap_type *bitmap, char *pngFilename);
89
90 #endif
```

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