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**ENHANCEMENT OF TRANSPORTATION NETWORK
ANALYSIS TOOLS FOR TRUCK-RELATED PLANNING
AND OPERATIONS
PART B**

Final Report

by

Scott S. Washburn
swash@ce.ufl.edu
<https://swash.essie.ufl.edu>
University of Florida

Wei Sun
w.sun2014@ufl.edu
University of Florida

for

Freight Mobility Research Institute (FMRI)
777 Glades Rd.
Florida Atlantic University
College Park, MD 20742

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<p>16. Abstract:</p> <p>Freeway network analysis tools often use simplified link performance functions to relate travel time to traffic demand. Such functions are typically not sensitive to the level of commercial truck presence in the traffic stream and are therefore of limited value in analyzing freeway network level operational policies that need to explicitly consider commercial truck traffic (e.g., truck lane restrictions or truck-only lanes). Furthermore, travel time reliability (TTR) is taking on increased emphasis in traffic operations analyses.</p> <p>Microsimulation is a tool that can potentially be used for network-level analyses, but when combined with TTR analysis, the computational burden can be problematic. The Highway Capacity Manual (HCM) freeway facility TTR analysis methodology is less computationally intensive than microsimulation and is more sensitive to traffic stream vehicle composition than typical network analysis link performance functions. However, this methodology is currently only applicable at the facility, not network, level.</p> <p>This project extends the HCM freeway TTR analysis methodology to the network level by integrating user equilibrium (UE) traffic assignment. The proposed freeway network TTR analysis methodology generates scenarios that represent the impacts of origin-destination (OD) demand variation, weather events, incident events, and work zone events on the freeway network. For each scenario, UE traffic assignment is performed for the freeway network, and the method of successive average (MSA) is applied to solve the UE traffic assignment. Travel times (and/or other performance measures) obtained from all the scenarios are aggregated into various distributions of interest, such as the network-, facility-, and OD-level distributions, and TTR performance measures are calculated at the three different levels.</p> <p>In addition, a software tool was developed based on the revision and integration of two existing software programs. The software tool provides a convenient and efficient approach for transportation planners and researchers to conduct the freeway network TTR analysis methodology.</p>			
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TABLE OF CONTENTS

EXECUTIVE SUMMARY	1
1.0 INTRODUCTION.....	3
1.1 BACKGROUND	3
1.2 PROJECT OBJECTIVE AND TASKS	3
2.0 FREEWAY NETWORK TRAFFIC ASSIGNMENT	5
2.1 METHODOLOGY	5
2.1.1 Freeway Network Representation.....	5
2.1.2 User Equilibrium Traffic Assignment	5
2.1.3 HCM Freeway Facility Core Methodology	6
2.1.4 Method of Successive Average (MSA) Approach.....	7
3.0 FREEWAY NETWORK TTR ANALYSIS	9
3.1 METHODOLOGY	9
3.1.1 Overview.....	9
3.1.2 Freeway Network TTR Analysis Time and Space Domain.....	9
3.1.3 Freeway Network TTR Scenario Generation	9
3.1.3.1 Stage 1. Scenarios and OD Demand Combinations	9
3.1.3.2 Stage 2. Work zone events.....	11
3.1.3.3 Stage 3. Weather events	13
3.1.3.4 Stage 4. Incident events.....	14
3.1.4 Travel Time Distribution and TTR Performance Measures	18
3.1.4.1 Travel Time Distribution.....	18
3.1.4.2 TTR Performance Measures	18
4.0 SOFTWARE DEVELOPMENT	19
4.1 OVERVIEW	19
4.2 REVISIONS AND INTEGRATIONS.....	19
4.2.1 Generate freeway network base files in XXE.....	19
4.2.2 Freeway network UE traffic assignment in XXE	19
4.2.3 Freeway network TTR scenario generation in HCM-CALC TTR/ATDM module .	19
4.2.4 Run freeway network TTR scenario analysis	20
4.2.5 Software implementation flow.....	20
4.3 EXAMPLE FREEWAY NETWORK TTR ANALYSIS IMPLEMENTATION	20
4.3.1 Freeway network.....	20
4.3.1.1 XXE freeway network node numbering.....	21
4.3.1.2 XXE node-link input.....	22
4.3.1.3 XXE OD data input	24
4.3.2 Freeway network TTR scenario generation.....	26
4.3.2.1 OD demand combinations.....	27
4.3.2.2 Weather events	28
4.3.2.3 Incident events	30
4.3.2.4 Work zone events.....	32
4.3.2.5 Scenario list	34
4.3.3 TTR scenario analysis.....	34
4.3.3.1 Analysis settings.....	34

4.3.3.1 Scenario results.....	35
4.3.3.2 Overall TTR results.....	36
4.3.3.1 Run time	38
5.0 CONCLUSION	39
5.1 OVERVIEW	39
5.2 CURRENT LIMITATIONS	39
5.2.1 HCM freeway facility TTR analysis methodology.....	39
5.2.2 Freeway facility spatial limit	40
5.2.3 Freeway facility starts with basic segment	40
5.2.4 LOS F not allowed in the first and last time period/segment	40
5.2.5 MSA approach	40
5.3 RECOMMENDATIONS FOR FURTHER RESEARCH	40
5.3.1 Freeway facility TTR analysis methodology.....	40
5.3.2 HCM freeway facility core methodology	40
5.3.3 Network traffic assignment.....	40
5.3.4 Software efficiency	41
6.0 REFERENCES.....	43

LIST OF FIGURES

Figure 1: Freeway network scheme	5
Figure 2: Facility travel time and flow relationship.....	7
Figure 3: Software implementation flow chart	20
Figure 4: Example freeway network scheme.....	21
Figure 5: Example freeway network numbering in XXE	22
Figure 6: Example freeway network node-link input (link 1 to 42) in XXE	23
Figure 7: Example freeway network node-link input (link 43 to 82) in XXE	23
Figure 8: Freeway facility settings in HCM-CALC FF module	24
Figure 9: Example freeway network OD data input (entry 1 to 46) in XXE.....	25
Figure 10: Example freeway network OD data input (entry 47 to 90) in XXE.....	26
Figure 11: Freeway network base file loaded in HCM-CALC TTR/ATDM	27
Figure 12: OD demand combinations input (zone 1 to zone 2) in HCM-CALC TTR/ATDM	28
Figure 13: Weather events settings in HCM-CALC.....	29
Figure 14: List of weather events generated in HCM-CALC.....	29
Figure 15: Weather events charts in HCM-CALC	30
Figure 16: Incident event input in the HCM-CALC	31
Figure 17: List of incident events of a specific freeway facility in HCM-CALC	31
Figure 18: Incident events chart in HCM-CALC	32
Figure 19: Work zone input in HCM-CALC	33
Figure 20: List of work zone events for a specific freeway facility in HCM-CALC	33
Figure 21: List of network scenarios generated in HCM-CALC.....	34
Figure 22: Analysis settings in HCM-CALC.....	35
Figure 23: Run scenario analysis in HCM-CALC	35
Figure 24: List of scenario results.....	36
Figure 25: Network level TTR performance measures in HCM-CALC	37

Figure 26: Facility level TTR performances in HCM-CALC 37
Figure 27: OD level TTR performance measures in HCM-CALC..... 38

EXECUTIVE SUMMARY

The state-of-the-art in traffic operations analysis methods that explicitly consider the impacts of large trucks has improved considerably over the last decade. Micro-simulation tools and deterministic analytic methods such as those in the Highway Capacity Manual (HCM) offer reasonably robust methods for explicitly accounting for large trucks.

However, there are still several areas where improvements in the methods and the tools are needed. Two areas in particular are: network-level analysis and travel time reliability (TTR) analysis, and even more so, the combination of these two areas. Conducting the network-level analysis entails the modeling of traffic assignment that can accurately forecast the truck flow distribution. However, most of the existing models do not work well due to their restrictive assumption that the passenger car equivalent (PCE) value of trucks is flow-independent; i.e., the PCE value is given and does not vary with traffic conditions. Although this simplifies the model, such an assumption is not consistent with the HCM and is very limiting. On the other hand, while micro-simulation is very suitable for performing network-level analysis, the computational burden can become unreasonable when TTR analysis is factored in, as this will increase the number of simulation runs several-hundred fold. In addition, network level analysis typically uses a relatively simple link performance function to represent the travel time and flow rate relationship. Such functions are not generally sensitive to the range of geometric and traffic conditions that can influence freeway facility operations. The HCM includes methods for analyzing freeway TTR that applies the HCM freeway facility core methodology, which can better represent traffic conditions than link performance functions, such as more sensitivity to impacts of large trucks through multivariate influences on PCE and more flexibility with lane configurations (e.g., managed lanes). However, this methodology is currently only applicable at the facility level. Even with macro-simulation methods, the network level TTR analysis is usually large-scale and computationally intensive, which makes a software tool the only feasible option to conduct the analysis.

The objective of this project was to improve the state-of-the-art for accounting for the impact of trucks at the network level, which is accomplished in the following two tasks.

- 1) Extend the methodology for multiclass user-equilibrium (UE) traffic assignment to account for flow-dependent PCEs of trucks.
- 2) Combine the HCM freeway facility TTR analysis methodology with the UE traffic assignment and extend it to the network level.

The details of the two tasks are documented in two separate reports, and this report focuses on the second task of the project, which is to extend the HCM freeway facility TTR analysis methodology into the network level. This task was accomplished through the following steps.

- 1) Apply the HCM freeway facility core analysis methodology to represent travel time and flow relationship in the UE traffic assignment methodology instead of the traditional link performance functions.
- 2) Combine the HCM freeway facility TTR analysis methodology with the UE traffic assignment and extend it to the network level.
- 3) Develop a software tool to implement the proposed methodology using C# on the .NET Framework based on the integration and revisions of two existing software programs.
- 4) Perform example implementation of freeway network TTR analysis and check the efficiency of the software tool.

1.0 INTRODUCTION

1.1 BACKGROUND

The state-of-the-art in traffic operations analysis methods that explicitly consider the impacts of large trucks has improved considerably over the last decade. Micro-simulation tools and deterministic analytic methods such as those in the Highway Capacity Manual (HCM) offer reasonably robust methods for explicitly accounting for large trucks.

However, there are still several areas where improvements in the methods and the tools are needed. Two areas in particular are: network-level analysis and travel time reliability (TTR) analysis, and even more so, the combination of these two areas. Conducting a network-level analysis entails the modeling of traffic assignment that can accurately forecast the truck flow distribution. However, most of the existing network analysis models do not work well due to their restrictive assumption that the passenger car equivalent (PCE) value of trucks is flow-independent; i.e., the given PCE value does not vary with traffic conditions. Such an assumption is not consistent with the HCM, although it can simplify the model. On the other hand, while micro-simulation is very suitable for performing network-level analysis, the computational burden can become unreasonable when TTR analysis is factored in, as this will increase the number of simulation runs several-hundred fold. In addition, network level analysis typically uses a relatively simple link performance function to represent the travel time and flow rate relationship. Such functions are not generally sensitive to the range of geometric and traffic conditions that can influence freeway facility operations. The HCM includes methods for analyzing freeway TTR that applies the HCM freeway facility core methodology, which can better represent traffic conditions than link performance functions, such as more sensitivity to impacts of large trucks through multivariate influences on PCE and more flexibility with lane configurations (e.g., managed lanes). However, this methodology is currently only applicable at the facility level. Even with macro-simulation methods, the network level TTR analysis is usually large-scale and computationally intensive, which makes a software tool the only feasible option to conduct the analysis.

1.2 PROJECT OBJECTIVE AND TASKS

This project aimed to improve the state-of-the-art for accounting for the impact of trucks at the network level. The two main objectives of the project were:

- 1) Extend the methodology for multiclass user-equilibrium (UE) traffic assignment to account for flow-dependent PCEs of trucks.
- 2) Combine the HCM freeway facility TTR analysis methodology with the UE traffic assignment and extend it to the network level.

The details of accomplishing these two objectives are documented in two separate reports, and this report (Part B) focuses on the second objective of the project, which is to extend the HCM freeway facility TTR analysis methodology into the network level. Additionally, since the methodology is data intensive and computationally intensive, a software tool to implement the methodology was also developed as part of this project. The objective discussed in this report was accomplished through completion of the following tasks.

-
- 1) Apply the HCM freeway facility core analysis methodology to represent travel time and flow relationship in the UE traffic assignment methodology instead of the traditional link performance functions.
 - 2) Combine the HCM freeway facility TTR analysis methodology with the UE traffic assignment and extend it to the network level.
 - 3) Develop a software tool to implement the proposed methodology using C# and the .NET Framework based on the integration and revision of two existing software programs.
 - 4) Perform an example freeway network TTR analysis implementation and check the computational efficiency of the software tool.

2.0 FREEWAY NETWORK TRAFFIC ASSIGNMENT

2.1 METHODOLOGY

2.1.1 Freeway Network Representation

The freeway network scheme of the proposed methodology includes nodes and links. There are two kinds of nodes--traffic analysis zone (TAZ) centroids, which produce and attract the traffic demand of the freeway network, and the network nodes, which connect the links of the freeway network. Each link in the freeway network represents a freeway facility defined by the HCM (2016), which is further composed of multiple segments. Traffic demands among the TAZ centroids are the origin-destination (OD) demands of the freeway network, and the node-link structure specifies the freeway network that connects the TAZ centroids. Figure 1 illustrates an example freeway network as represented by the link-node structure.

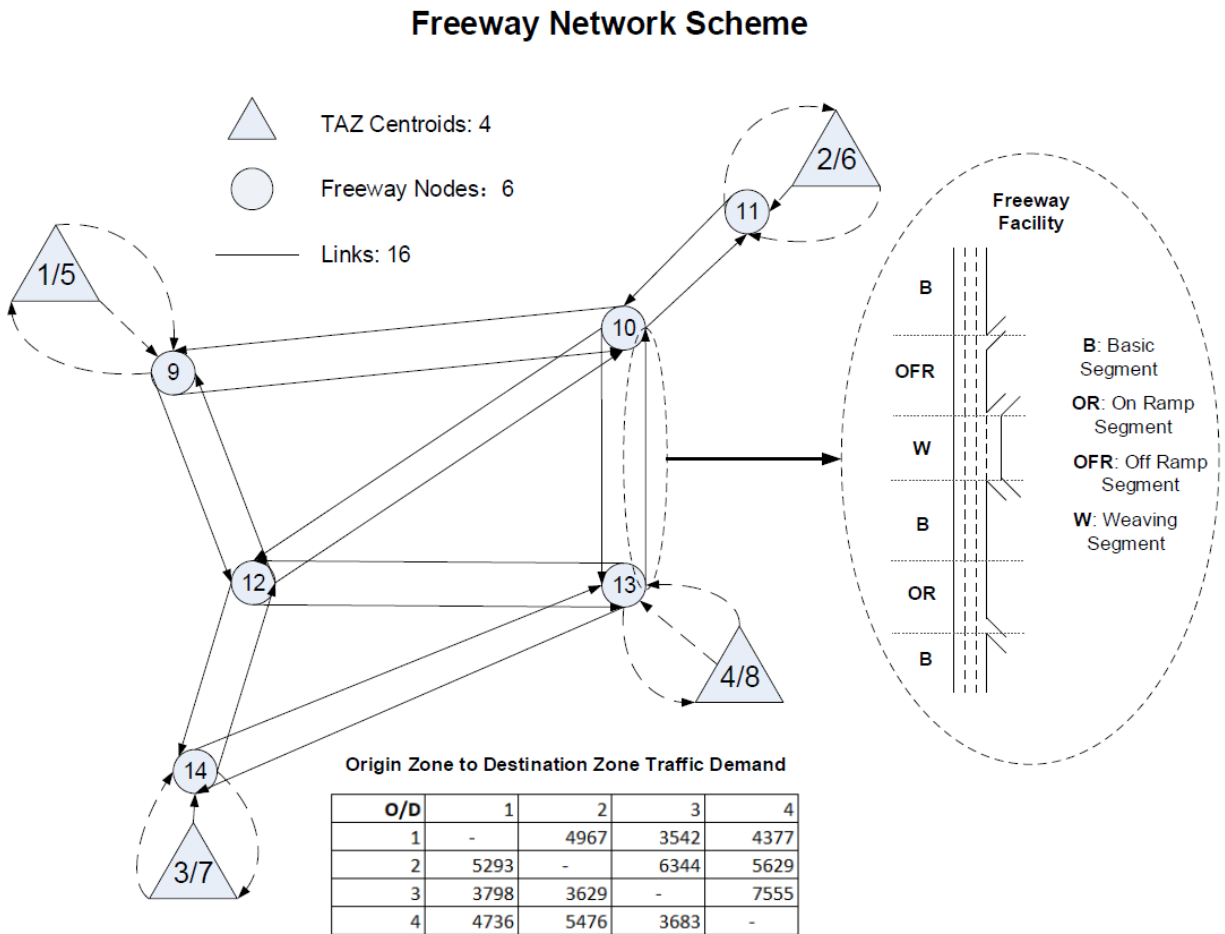


Figure 1: Freeway network scheme

2.1.2 User Equilibrium Traffic Assignment

With the uncertainties brought by the TTR influential factors, it is critical to have a traffic assignment model that can assign traffic to the links in the network in a way that represents the

route choices of the road users. Wardrop (1952) proposed user equilibrium of a traffic network under the assumption that each user tends to minimize his/her travel time, and user equilibrium is achieved when no user can reduce his/her travel time by changing route. UE traffic assignment model has been widely used for network traffic assignment.

Most UE traffic assignment studies apply link performance functions, such as the Bureau of Public Roads (BPR) function, to represent the relationship between travel time and flow rate, as shown in Equation (1).

$$t_{\alpha} = t_{\alpha}^0 \left(1 + 0.15 \left(\frac{v_{\alpha}}{c_{\alpha}} \right)^4 \right) \quad (1)$$

t_{α} is the average travel time of link α

t_{α}^0 is the free-flow travel time of link α

v_{α} is the traffic volume of link α

c_{α} is the capacity of link α

The approaches for solving UE traffic assignment are based on the aggregation of estimated values from link performance functions, of which the functions are required to be non-decreasing, continuous and differentiable. Beckmann et al. (1956) proposed the mathematical programming formulation of UE traffic assignment, which formulated the problem as a convex problem with a convex objective function under linear constraints. Dafermos and Sparrow (1969) applied the Frank-Wolfe algorithm to solve this convex problem. While the use of such a simple link performance function would shorten the computational time to identify the point of user equilibrium, the accuracy of the link performance function with respect to the representation of freeway facility traffic conditions would directly dictate the accuracy of the network TTR analysis. Furthermore, these simple link performance functions generally lack elements that make them more sensitive to the roadway and traffic conditions of the freeway facility.

2.1.3 HCM Freeway Facility Core Methodology

The freeway facility core methodology in Chapter 10 of the HCM 6th edition (TRB, 2016) is a freeway facility level macro-simulation methodology, which is the state-of-the-art methodology for macroscopic freeway facility analysis. The methodology is capable of analyzing the studied freeway facility under both undersaturated and oversaturated conditions, as well as over space (continuous analysis of different segments, such as basic, weaving, merge and diverge segments) and time (continuous analysis in the unit of 15-minute time period). There have been many applications of the methodology, demonstrating the validity of the methodology to accurately represent the real life traffic conditions of freeway facilities (e.g., Schroeder and Roupail, 2010; Schroeder *et al.*, 2012). Hall et al. (2000) applied the HCM freeway facility core methodology and three micro-simulation models (CORSIM, FREQ, and INTEGRATION) for the analysis of six freeway sites and compared the results with field data. It was found that the HCM freeway facility core methodology performed as well as the micro-simulation models. In this case, this research proposes to use the HCM freeway facility core methodology for link travel time calculation in the UE traffic assignment.

Unlike the link performance functions in traditional UE traffic assignment, such as the BPR function, which are continuous, non-decreasing, and differentiable, the HCM freeway facility core methodology is a macro-simulation methodology. For the latter case, a sensitivity analysis was conducted with respect to the relationship between the facility mainline traffic demand and the resulting average facility travel time. Results from the analysis suggest that the relationship

between the facility mainline traffic demand and the facility average travel time varies among different freeway network settings, and does not always follow a consistent form, as shown in Figure 2.

Since the HCM freeway facility core methodology requires that the length of the freeway facility should be less than the distance a vehicle traveling with the average speed can achieve in 15 min, which is around 9 to 12 miles. In this case, during the freeway network setup, links that are longer than the spatial limit need to be divided into several links. The HCM freeway facility core methodology requires that the facility start and end with basic segments, which should also be considered during the freeway network setup.

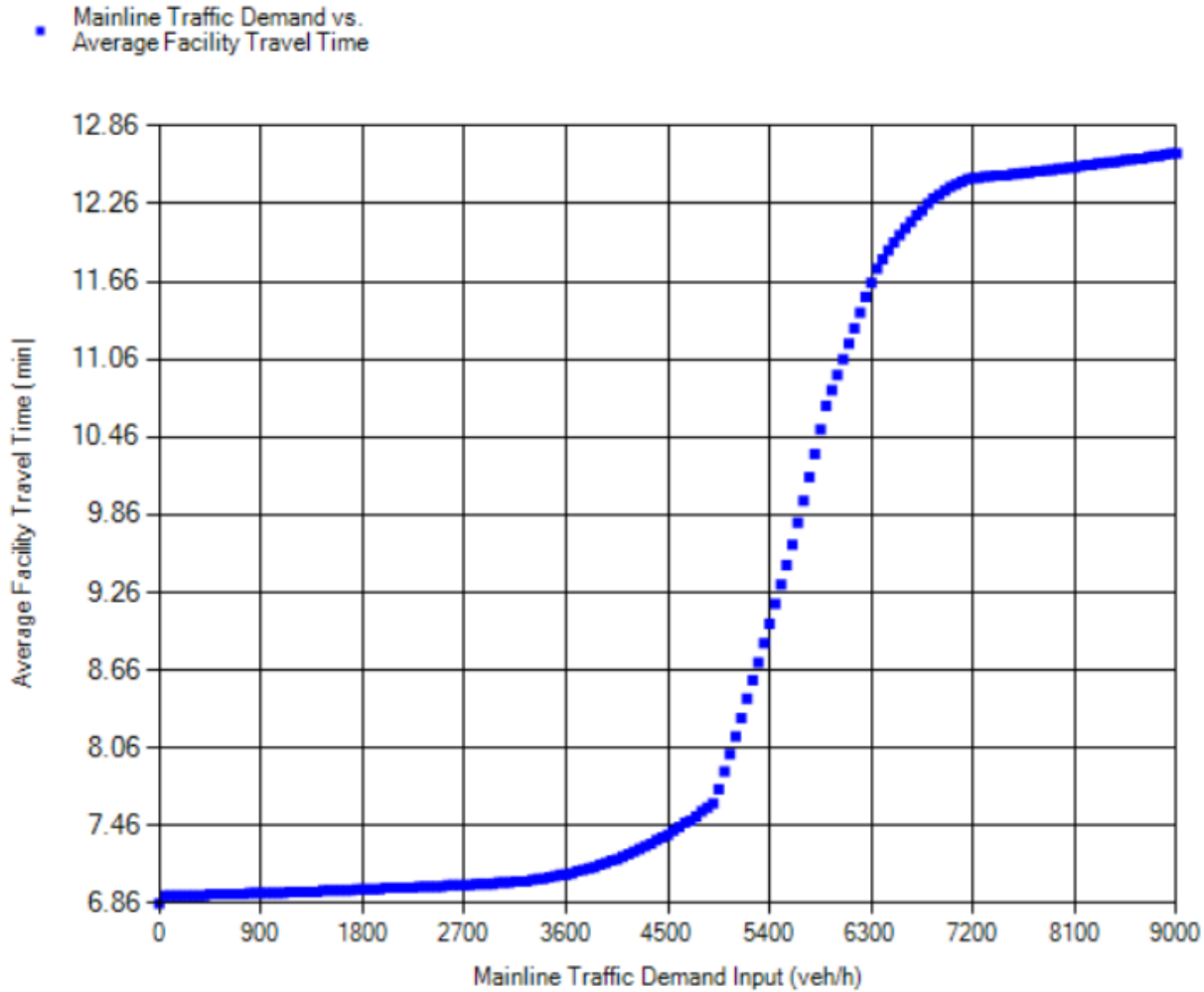


Figure 2: Facility travel time and flow relationship

2.1.4 Method of Successive Average (MSA) Approach

Sheffi (1985) first proposed the Method of Successive Average (MSA) approach for solving the UE traffic assignment problem. Because of the simplicity of the algorithm, which does not require explicitly defined link performance functions, the MSA approach has been widely used for simulation-based UE traffic assignment applications. This project used the MSA approach to solve the UE traffic assignment while using the HCM freeway facility core methodology for link travel time calculation.

The steps for the MSA approach to solve the freeway network UE traffic assignment in this project are as follows (note that a is the link index, t_a is the travel time of link a , x_a^i is the volume of link a of iteration i , y_a^i is the (direction) volume of link a of iteration i , ε is the convergence criteria value):

Step 0. Initialization. Perform all-or-nothing assignment based on freeway flow travel time of the links provided by the HCM freeway facility core methodology: $t_a = t_a(0), \forall a$. (The all-or-nothing assignment assign all trips to links comprising the shortest paths, and to find the shortest path between OD pairs, this project applies the Dijkstra's algorithm.) This yields x^1 , which is the initial set of link volumes. Set iteration counter $n := 1$

Step 1. Update link travel time. Apply the HCM freeway facility core methodology to obtain link travel times with the link volumes of the current iteration: $t_a^n = t_a(x_a^n), \forall a$.

Step 2. Direction finding. Perform all-or-nothing assignment based on the updated link travel times: $t_a^n, \forall a$. This yields (direction) link volumes y^n .

Step 3. Move. Set the new set of link volumes to be: $x_a^{n+1} = x_a^n + (\frac{1}{n})(y_a^n - x_a^n)$.

Step 4. Convergence Criterion. Check if the link volumes converge between the current iteration and the last iteration. If $\frac{\sqrt{\sum_a (x_a^{n+1} - x_a^n)^2}}{\sum_a x_a^n} < \varepsilon$, stop; else, set iteration counter $n := n + 1$ and go to Step 1.

3.0 FREEWAY NETWORK TTR ANALYSIS

3.1 METHODOLOGY

3.1.1 Overview

The freeway network TTR analysis methodology extends the HCM freeway facility TTR analysis methodology to the network level. The essence of performing a freeway network TTR analysis is to obtain the travel time distribution aggregated from the scenarios of the studied freeway network, from which the TTR performance measures are calculated and analyzed. The facility level methodology in the HCM generates scenarios that represent the effects of demand variation, weather events, incident events and work zone events of the facility, and then calculates facility travel time of each scenario with HCM freeway facility core methodology to obtain the travel time distribution.

For the network level methodology, the origin-destination (OD) demands of the traffic analysis zones (TAZ) are studied and the traffic assignment model is used to assign volume to facilities based on the OD demands. In this case, the freeway network TTR analysis methodology generates scenarios that consider the effects of OD demand variation, weather events, incident events, and work zone events on the freeway network. Then the methodology performs a UE traffic assignment for each scenario to obtain the travel times of facilities within the network, during which the HCM freeway facility core methodology is applied to represent the facility travel time and flow relationship. Finally, travel times of all the scenarios are aggregated into travel time distributions and TTR performance measures are calculated for analysis.

3.1.2 Freeway Network TTR Analysis Time and Space Domain

The time domain of the methodology includes the reliability reporting period (RRP), study period, and analysis period. The RRP is the specific set of days to measure TTR, which is usually a full year. The study period is the time interval during the day that the freeway network is evaluated, which is usually the peak period (e.g., 3 PM – 7 PM). The analysis period is the interval of time to which a single application of the HCM freeway facility core methodology is applied, typically 15 minutes.

The space domain of the methodology is the same as the freeway network representation described in Chapter 2. The freeway network includes nodes and links, and links represent HCM-defined freeway facilities.

3.1.3 Freeway Network TTR Scenario Generation

The freeway network TTR scenario generation methodology is based on the freeway facility TTR scenario generation methodology in the HCM 6th edition (TRB, 2016), which is the hybrid methodology proposed by the NCHRP Project 03-115 (Aghdashi et al., 2015). The freeway network TTR scenario generation includes 4 stages and 24 steps, which generates scenarios that represent the impacts of influential factors, such as OD demand combinations, weather events, incident events, and work zone events on the travel times of the freeway network.

3.1.3.1 Stage 1. Scenarios and OD Demand Combinations

As stated in the freeway network representation, the traffic demand among the TAZ centroids specifies the OD demand data of the freeway network. In this stage, OD demand

combinations, the combinations of day-of-week and month-of-year demand variations, are specified for each OD pair, the number of scenarios are generated based on the number of demand combinations, and scenario probabilities are calculated based on number of days associated with the scenario.

Step 1. Freeway network data input

In this step, the freeway network data input is provided describing the freeway network's traffic demand and roadway geometry for a single study period. The file that contains these data is called the base (or seed) file. Typically, the analyst enters the annual average traffic demands in the base file, although it is possible to enter other demands and adjust for these values relative to the annual average values later with a factor in the demand scenario module. The data input should include the overall network data (nodes, links, TAZ centroids, and OD traffic data) and as stated in the freeway network scheme, the links are represented as freeway facilities, so the input data for HCM freeway facility core methodology for the related freeway facilities are also required for each link. Details of the required data for HCM freeway facility core methodology are documented in HCM Chapters 10 and 25 (TRB, 2016).

Step 2. Number of OD demand combinations and scenarios

The HCM defines a demand combination as the combination of a specific weekday and month of the year. For each OD pair in the freeway network, the demand combinations are specified. For a one year and weekday only TTR analysis, the number of demand combinations, denoted as N_{dc} , is: 5 (weekdays) \times 12 (months) = 60 (demand combinations).

As each demand combination usually contains 4 to 5 calendar days, by default the HCM recommend the scenario replications number, denoted as n_r , to be four to generate the number of scenarios that represent the RRP of one year. For a one year and weekday only TTR analysis, the total number of scenarios, denoted as N_{scen} , is: $N_{scen} = N_{dc} (60) \times n_r (4) = 240$.

However, when it comes to short RRP duration, the number of replications should be increased to capture the variability in the travel time distribution. Guidance on the recommended number of replications in such cases is provided in HCM Chapter 11 Exhibit 11-9.

Step 3. Calculate demand level for each OD pair of each scenario

For each OD pair, the demand multipliers represent the day of week and month of year variations of the OD demand. Demand multipliers should be calculated from OD demand data of the study period for the entire RRP. Each scenario corresponds to one demand combination, and the demand multiplier of the demand combination represents the demand level of the scenario. The demand level of the OD demand of a scenario is adjusted by the demand adjustment factor (DAF). DAF of the scenario is calculated by Equation (2).

$$DAF_s^{OD} = DM^{OD}(s)/DM^{OD}(seed) \quad (2)$$

DAF_s^{OD} is the DAF associated with scenario s

$DM^{OD}(s)$ is the demand multiplier of the demand combination associated with scenario s
 $DM^{OD}(seed)$ is the demand multiplier associated with the base file

Step 4. Calculate scenario probabilities

The probability of a scenario is the number of days for the demand combination associated with the scenario divided by the product of number of days in the RRP and number of scenario replications, and it can be calculated by Equation (3). (HCM Equation 25-73)

$$P_s = \frac{n_{dc}(s)}{4 \times N} \quad (3)$$

$n_{dc}(s)$ is the number of days in demand combination dc associated with scenario s
 N is the number of days in RRP

3.1.3.2 Stage 2. Work zone events

In this stage, scheduled work zone events of each freeway facility in the network are assigned to specific scenarios. For each freeway facility, the influence of work zone (calculation of adjustment factors) follows the work zone analysis methodology documented in HCM Chapter 10 and the assignment of work zone events follows the HCM freeway facility TTR scenario generation methodology documented in the HCM Chapter 25. Required data and source for work zone input can be found in HCM Chapter 11.

Step 5. Calculate work zone event adjustment factors

According to the work zone analysis methodology in HCM Chapter 10, the impacts of a work zone event on a freeway facility segment are affected by work zone characteristics, such as the lane closure type, barrier type, area type, lateral distance, and daytime/nighttime operations.

The lane closure severity index, denoted as $LCSI$, represents the lane closure configuration of a work zone event. It is calculated by Equation (4). (HCM Equation 10-7)

$$LCSI = \frac{1}{OR \times N_o} \quad (4)$$

OR is the ratio of the number of open lanes to the total number of lanes of the affected segment

N_o is the number of open lanes in the work zone

The queue discharge rate, denoted as QDR , is a function of the work zone configuration and other prevailing conditions. It is calculated by Equation (5). (HCM Equation 10-8)

$$QDR_{wz} = 2,093 - 154 \times LCSI - 194 \times f_{BR} - 179 \times f_{AT} + 9 \times f_{LAT} - 59 \times f_{DN} \quad (5)$$

f_{BR} is the indicator variable for barrier type (0 for concrete and hard barrier separation, and 1 for other soft barrier separation, such as cone, and plastic drum)

f_{AT} is the indicator factor for area type (0 for urban areas and 1 for rural areas)

f_{LAT} is the lateral distance from the edge of travel lane adjacent to the work zone to the barrier, barricades, or cones (0-12 ft)

f_{DN} is the indicator factor for daylight or night operations (0 for daylight, and 1 for night)
 The work zone capacity, denoted as C_{wz} , is calculated by the Equation (6) (HCM Equation 10-9)

$$C_{wz} = \frac{QDR_{wz}}{100 - \alpha_{wz}} \times 100 \quad (6)$$

α_{wz} is the percentage drop in prebreakdown capacity at the work zone due to queuing conditions (%)

The work zone free-flow speed, denoted as FFS_{wz} , is calculated by the Equation (7). (HCM Equation 10-10)

$$FFS_{wz} = 9.95 + 33.49 \times f_{Sr} + 0.53 \times SL_{wz} - 5.60 \times LCSi - 3.84 \times f_{Br} - 1.71 \times f_{DN} - 8.7 \times TRD \quad (7)$$

f_{Sr} is the speed ratio of non-work zone speed limit to work zone speed limit

SL_{wz} is the indicator factor

The work zone event affects the freeway facility segments by capacity adjustment factor (CAF) and speed adjustment factor (SAF). The corresponding CAF_{wz} and SAF_{wz} can be calculated by Equation (8) and (9), respectively. (HCM Equation 10-11 and 10-12, respectively) Note that in common sense the freeway free-flow speed under work zone event should be less than normal conditions, so that the CAF and SAF for work zone event should not be greater than 1.0.

$$CAF_{wz} = \frac{c_{wz}}{c} \quad (8)$$

c is the basic freeway segment capacity under normal conditions (pc/h/ln)

c_{wz} is the work zone capacity (pc/h/ln)

$$SAF_{wz} = \frac{FFS_{wz}}{FFS} \quad (9)$$

FFS is the freeway free-flow speed under normal conditions (mi/h)

Step 6. Calculate demand combination active work zone ratios

For any unassigned work zone event, for each affected demand combination, calculate the active work zone ratio, denoted as r_{dc} . The ratio is calculated by Equation (10).

$$r_{dc} = \frac{n_{dc}^{wz}}{n_{dc}} \quad (10)$$

n_{dc}^{wz} is the number of days in the RRP associated with the demand combination dc that the work zone event is active

n_{dc} is the number of days in the RRP associated with the demand combination dc

Step 7. Calculate the number of active work zone scenarios

For each demand combination affected by the current work zone event, calculate the number of scenarios associated with the work zone event, denoted as N_{dc}^{wz} . This is calculated by Equation (11) work zone event, for each affected demand combination,

calculate the active work zone ratio, denoted as r_{dc} . The ratio is calculated by Equation (11). (HCM Equation 25-74)

$$N_{dc}^{wz} = \mathit{round}(r_{dc} \times n_r) \quad (11)$$

Step 8. Assign scenarios to the current work zone event

According to the number of scenarios associated with the current work zone event, randomly assign the scenarios to the affected demand combinations, the scenarios associated with any demand combination have equal probability during the random assignment.

Step 9. Assign scenarios to the current work zone event

According to the number of scenarios associated with the current work zone event, randomly assign the scenarios to the affected demand combinations, the scenarios associated with any demand combination have equal probability during the random assignment. Overlap between work zone events within the same scenario on the same segment is not allowed. If overlap exists, then redo the latest scenario assignment.

Repeat Step 5 to 9 until all work zone events of the current freeway facility are assigned to scenarios, and do this for all freeway facilities in the network.

3.1.3.3 Stage 3. Weather events

As the research assumes that weather events affect all the facilities in the freeway network, the methodology for freeway network weather events follows the freeway facility TTR scenario generation methodology in HCM Chapter 25 (TRB, 2016). In this stage, weather events are generated on a monthly basis. First, the expected weather event frequencies for a month are calculated based on monthly weather probabilities. Second, the generated weather events are randomly assigned to the scenarios in the current month. Then, the weather events are randomly assigned to the time periods of the study period of the associated scenario. Finally, repeat the above procedure for every month that the RRP includes.

Step 10. Weather data input

The following is a brief overview of the weather data input, the required data preparation for weather events is documented in HCM Chapter 11 (TRB, 2016).

The weather data for the area of the freeway network should be collected and classified into weather categories, such as medium rain, heavy rain, light snow, light-medium snow, medium-heavy snow, heavy snow, severe cold, low visibility, very low visibility, minimal visibility, and non-severe weather (Normal). Weather data for each category should include monthly probability, average duration, and adjustment factors (DAF, CAF and SAF).

The monthly probabilities of weather category can be calculated as the sum the all study period durations that the weather are present in the month divided by the sum of all study period durations in the month. (HCM Equation 25-75)

$$P_w(w, i) = \frac{\text{Sum of all SP durations (min) in month } i \text{ that weather type } w \text{ is present}}{\text{Sum of all SP durations (min) in month } i} \quad (12)$$

If analysts do not have access to the detailed local weather data to estimate the weather probabilities, they can use the 10-year average weather probabilities for metropolitan areas in HCM Volume 4 Technical Reference Library (TRB, 2016).

Step 11. Expected frequency of weather events for the current month

As each scenario corresponds to a demand combination, which represents a combination of a specific day and month, so the scenarios of the current month can be selected. Then, the expected weather event frequency $E_{w,i}$ of weather type w in month i can be calculated by Equation (13).

$$E_{w,i} = \text{Round}\left(\frac{P_{w,i} \times D_{SP} \times n^i}{D_w}\right) \quad (13)$$

$P_{w,i}$ is the time-wise weather event probability of weather type w in month i

D_{SP} is the duration of study period in hours

n^i is the number of scenarios associated with month i

D_w is the expected duration of the weather type w rounded to the nearest 15 minutes and expressed in hours

Associate generated weather events with their durations, DAFs, CAFs, and SAFs to obtain a list of weather events.

Step 12. Update the list of weather events for the current month

For each weather event, first, randomly assign the scenarios of the current month to the weather event based on the scenario probabilities; second, randomly assign the start times (from the time periods in the study period) to the weather event, the start times of weather events are assigned randomly based on a uniform distribution.

During the assignment process, check the scenario number, start time and weather duration of all the former weather events, to see if there is temporal overlap between weather events in the same scenario. Any time period of a scenario is not allowed to have more than one weather event. If there is overlap, redo the last weather event assignment, do this until all weather events in the current month are associated with scenarios and start times.

3.1.3.4 Stage 4. Incident events

In this stage, incident events are generated on a monthly basis and freeway facility basis, as incident rates vary among different month of the year as well as different freeway facilities in the network. For each freeway facility, the incident events generation and assignment follows the freeway facility TTR scenario generation methodology in HCM Chapter 25 (TRB, 2016). First, the incident events for the current freeway facility of the current month are generated based on monthly incident rates and distribution probability of each incident type. Second, the generated incident events are randomly assigned to the scenarios in the current month. Third, the incident events generated are then randomly assigned to segments in the current freeway facility and time periods in the study period of

the associated scenario, based on segment vehicle miles traveled and time period vehicle miles traveled, respectively. Finally, repeat the above procedure for every month that the RRP includes and every freeway facilities the network includes.

Step 13. Incident data input for the current facility

For each freeway facility in the network, the incident data should be collected and classified into incident categories, such as shoulder closure, one-lane closure, two-lane closure, three-lane closure, and four or more lane closure.

The distribution information of incident categories, denoted as $G(inc)$, should be collected, default distribution is as following. (HCM Equation 25-82)

$$G(inc) = \begin{cases} 0.75 & inc = 1 \\ 0.20 & inc = 2 \\ 0.05 & inc = 3 \\ 0.00 & inc = 4 \\ 0.00 & inc = 5 \end{cases} \quad (14)$$

inc is the incident category, 1 = shoulder closure, 2 = one-lane closure, 3 = two-lane closure, 4 = three-lane closure, 5 = four or more lane closure.

Incident data for each category should include average duration, standard deviation of duration, and adjustment factors (DAF, CAF and SAF). The required data preparation for incident events of a freeway facility is documented in the HCM Chapter 11 (TRB, 2016).

Step 14. Expected frequency of incident events of the current month of the current facility

The expected frequency, denoted as F_{ij} , per study period in month i and facility j can be calculated using Equation (15).

$$F_{ij} = IR_{ij} \times VMT_j \quad (15)$$

VMT_j is the vehicle miles traveled (VMT) of freeway facility j

IR_{ij} is the incident rate per 100 million VMT for month i facility j

Step 15. Generate a set of incident frequencies for scenarios in the current month

The number of incidents, denoted as k , in a study period follows the Poisson distribution, denoted as $P(k)$.

$$P(k) = \frac{F_{ij}^k}{k!} e^{-F_{ij}} \quad (16)$$

The number of scenarios, denoted as N_{ij}^k , that are assigned k incidents for month i and facility j can be calculated by Equation (17). (HCM Equation 25-81)

$$N_{ij}^k = \text{Round}\{F_{ij} \times P(k)\} \quad (17)$$

Step 16. List of incident events for the current facility

Repeat Step 14 and 15 for all the months included in the RRP, the list of incident events for the current facility is generated.

Step 17. Scenario assignment

For each month, randomly assign the scenarios of the month to the incident events of the month based on the scenario probabilities.

Step 18. Incident category distribution frequencies

The number of incidents, denoted as N_{inc} , of category inc can be calculated by Equation (18). (HCM Equation 25-83)

$$N_{inc} = N_{tot} \times G(inc) \quad (18)$$

N_{tot} is the total number of incidents generated

Step 19. Incident category assignment

Randomly assign incident category to the number of incidents generated based on the distribution of incident categories from Step 18.

Step 20. Generate incident durations by incident severity

The duration for each incident severity type follows a truncated lognormal distribution. For each incident type, a set of duration bins can be determined, usually with the bin interval of 15 minutes, then truncate the first and last bin interval depending on the range of the incident duration. For example, the duration of shoulder closure is from 8.7 to 52.5 min, the set of bin values can be 15, 30, 45, 60, the bin intervals are: (8.7, 22.5], (22.5, 37.5], (37.5, 52.5]. The probability of each bin can be calculated from Equation (19) and then normalize the probabilities to make the total to be 1.

$$P(d, \mu, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{(\ln d - \mu)^2}{2\sigma^2}\right], d > 0 \quad (19)$$

d is the set of incident durations (bin values) in 15 minutes (15, 30, 45...), decided by the incident duration range

μ is the parameter converted by the mean incident duration m

σ is the parameter converted by the standard deviation of incident duration v

Since the incident duration sample is not lognormal, the mean incident duration and standard deviation need to be converted to μ and σ , respectively, using Equations (20) and (21), respectively.

$$\mu = \ln\left(\frac{m}{\sqrt{1 + \frac{v}{m^2}}}\right) \quad (20)$$

$$\sigma = \sqrt{\ln\left(1 + \frac{v}{m^2}\right)} \quad (21)$$

Step 21. Incident duration assignment

Random assign incident durations to the incident events based on the probabilities from Step 20.

Step 22. Distribution of incident start time and location

The distribution of incident start times will coincide with the distribution of facility VMT across the analysis periods. Also, the distribution of incident locations will be tied to the distribution of study period VMT across segments.

Distribution of the incident location for segment seg , denoted as $P_1(seg)$, is calculated by Equation (22). (HCM Equation 25-88)

$$P_1(seg) = \frac{VMT_{seg}}{VMT_j} \quad (22)$$

VMT_{seg} is the VMT on a specific segment

VMT_j is the VMT of the current facility j

Distribution of the incident start time for time period tp , denoted as $P_2(tp)$, is calculated by Equation (23). (HCM Equation 25-89)

$$P_2(tp) = \frac{VMT_{tp}}{VMT_{SP}} \quad (23)$$

VMT_{tp} is the VMT of the assigned time period for the incident start time

VMT_{SP} is the VMT across all the time periods of the study period

Step 23. Incident start times and locations assignment

Number of incidents assigned a location (segment) seg , denoted as N^{seg} , is calculated by Equation (24). (HCM Equation 25-92)

$$N^{seg} = \mathbf{round}(N_{tot} \times P_1(seg)) \quad (24)$$

Number of incidents assigned a starting time (time period) tp , denoted as N^{tp} , is calculated by Equation (25). (HCM Equation 25-93)

$$N^{tp} = \mathbf{round}(N_{tot} \times P_2(tp)) \quad (25)$$

Step 24. Randomly assign incident start time and location

From the list of events, select an incident whose start time and location have not been assigned, and randomly assign a start time and location based on the probabilities and numbers calculated from Steps 22 and 23.

During the assignment process, check the scenario number, start time, location and incident duration of all the former incident events, to see if there is spatial and temporal overlap between incident events in the same scenario. Any time period of a scenario is not allowed to have more than one incident event at the same segment. If there is overlap, undo the last start time and location assignment; if there is no overlap, move to the next assignment. Repeat Steps 13 to 24 for all the freeway facilities of the network.

After the above steps a list of scenarios are generated, each scenario contains a specific network OD traffic demand data, list of work zone events, list of weather events, and list of incident events.

3.1.4 Travel Time Distribution and TTR Performance Measures

3.1.4.1 Travel Time Distribution

Once the list of scenarios is generated, iterate through each scenario and perform the UE traffic assignment for the freeway network affected by scenario-specific OD demand levels, weather events, incident events, and work zone events. Travel times (and/or other performance measures) obtained from all the scenarios can be aggregated into various distributions of interest, such as network-, facility-, and OD-level distributions, etc.

3.1.4.2 TTR Performance Measures

This project analyzes TTR performance measures at three different levels: network level, facility level, and OD level.

The network level TTR performance measure is the percentage of travel time index (TTI), which is calculated based on the travel times obtained for each freeway facilities in the network for all the scenarios.

The facility level TTR performance measures include travel time, TTI, vehicle miles traveled (VMT), vehicle hours traveled (VHT), average speed (mi/h), density (veh/mi/ln), and density (pc/mi/ln), which are calculated based on the performance measures of the specific facility for all the scenarios. Besides, semi-standard deviation, misery index, buffer index, and planning time index are also included for facility level TTR analysis.

The OD level TTR performance measures include the travel time and TTI statistics calculated from the shortest path travel time of the specific OD pair for all the scenarios. This project also summarizes the path level statistics of the specific OD pair, such as the utilization percentage, average travel time, minimum travel time, maximum travel time, and standard deviation of travel time for each path of the OD pair.

4.0 SOFTWARE DEVELOPMENT

4.1 OVERVIEW

As the proposed freeway network TTR analysis methodology is both data intensive and computationally intensive, it is only feasible for transportation practitioners to apply the methodology through a software tool. The software is developed based on the revision and integration of components from two existing software programs: XXE (Washburn and Mannering, 2007) and HCM-CALC (Washburn, 2015).

XXE is a traffic assignment software program that can perform standard UE traffic assignment. The program currently uses the Bureau of Public Roads (BPR) performance function for travel time calculation and the Frank-Wolfe approach to solve UE traffic assignment, as discussed in Section 2.1.2. HCM-CALC is a software program that implements the Uninterrupted Flow Analysis Methodologies of the HCM. The calculation modules relevant to this research include the Freeway Facility (FF) module, which implements the HCM freeway facility core methodology, and the Travel Time Reliability/Active Traffic & Demand Management (TTR/ATDM) module (Sun and Washburn, 2016; Sun, 2014), which implements the HCM freeway facility TTR analysis methodology.

4.2 REVISIONS AND INTEGRATIONS

In order to implement the proposed methodology, the software development includes the following major revisions and integrations of components from the two existing software programs.

4.2.1 *Generate freeway network base files in XXE*

XXE is revised to generate freeway network base files, which contains the data that represent the base condition of the freeway network in one study period. The base files include the network file, which contains the node-link information as well as freeway facilities input data, and the OD data file, which contains the base OD demand data of the freeway network.

4.2.2 *Freeway network UE traffic assignment in XXE*

XXE is revised to perform the freeway network UE traffic assignment. The MSA approach is added to XXE, during which, for the travel time and flow relationship, the XXE calls the HCM-CALC FF module to perform the HCM freeway facility core methodology.

4.2.3 *Freeway network TTR scenario generation in HCM-CALC TTR/ATDM module*

HCM-CALC TTR/ATDM module is revised to implement the freeway network TTR scenario generation methodology. The TTR/ATDM module is able to load the freeway network base files generated in XXE. The TTR/ATDM module also includes user interfaces to specify input for OD demand combinations, weather events, incident events, and work zones events of the freeway network. The TTR/ATDM module can generate freeway network TTR scenarios based on these user inputs.

4.2.4 Run freeway network TTR scenario analysis

HCM-CALC TTR/ATDM module is revised to assign scenario settings to the base freeway network loaded from the base files and perform UE traffic assignment with scenario specific freeway network settings. For each scenario, the TTR/ATDM module assign scenario specific OD demand combinations, weather events, incident events, and work zone events to adjust the base freeway network through relative adjustment factors (DAF, CAF, and SAF). The TTR/ATDM module calls XXE to perform UE traffic assignment with the scenario specific freeway network settings. The TTR/ATDM module collects traffic assignment results from each scenario and aggregates the scenario results to obtain TTR performance measures.

4.2.5 Software implementation flow

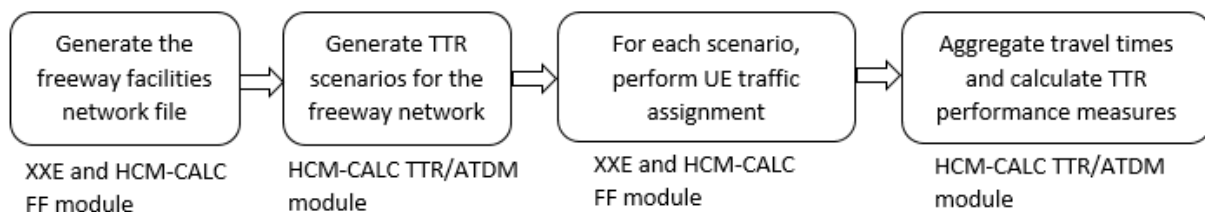


Figure 3: Software implementation flow chart

As shown in Figure 3, the freeway facilities network file is generated in XXE by calling the HCM-CALC FF module and then loaded into the HCM-CALC TTR/ATDM module. Then, the TTR/ATDM module generates TTR scenarios, applies adjustment factors to the freeway facilities in the network. After the scenario generation and assignment, the TTR/ATDM module calls upon the revised UE traffic assignment model in XXE to obtain facility travel times of the network, during this process, the XXE will call upon the HCM-CALC FF module to calculate link (facility) travel time. After the UE traffic assignments, assignment results of each scenario are obtained and the HCM-CALC TTR/ATDM module will aggregate the scenario results to obtain TTR performance measures of three levels: the network level, facility level, and the OD level.

4.3 EXAMPLE FREEWAY NETWORK TTR ANALYSIS IMPLEMENTATION

This project implements an example freeway network TTR analysis through the developed software tool, and the major steps of the implementation are summarized as following, which could also serve as a user guide of the software. During the implementation, revisions have been made to improve the user interface of the software, as well as the computational efficiency, so that transportation practitioners can conduct the freeway network TTR analysis in a convenient and efficient approach through the software tool.

4.3.1 Freeway network

The example freeway network contains 10 TAZ zones and 52 links (freeway facilities). Since the purpose of the implementation is to test the feasibility and efficiency of the software and revise it as needed, the input values are not based on field data, but mostly values specified by this project

as appropriate, and in some occasions, default values from the HCM. The freeway network base files are generated in the XXE as following.

4.3.1.1 *XXE freeway network node numbering*

Figure 4 shows the example freeway network with 10 traffic analysis zones and 13 freeway nodes connected by 52 freeway facility links. In XXE, the zones of the freeway network are represented by TAZ centroids (the triangles in Figure 4), and are consecutively numbered as origins 1 through 10. Besides serving as origins, each TAZ centroid also serves as a destination numbered 11 through 20, as shown in Figure 5. After the numbering of TAZ centroids, the freeway nodes may be numbered, and in this case, the freeway nodes of the example network are consecutively numbered 21 through 33. Then, access links are added between the TAZ centroids and the connecting freeway nodes, these links are not included in the analysis results, but are essential for the XXE network topology. Figure 5 shows the final numbering of the example freeway network for XXE.

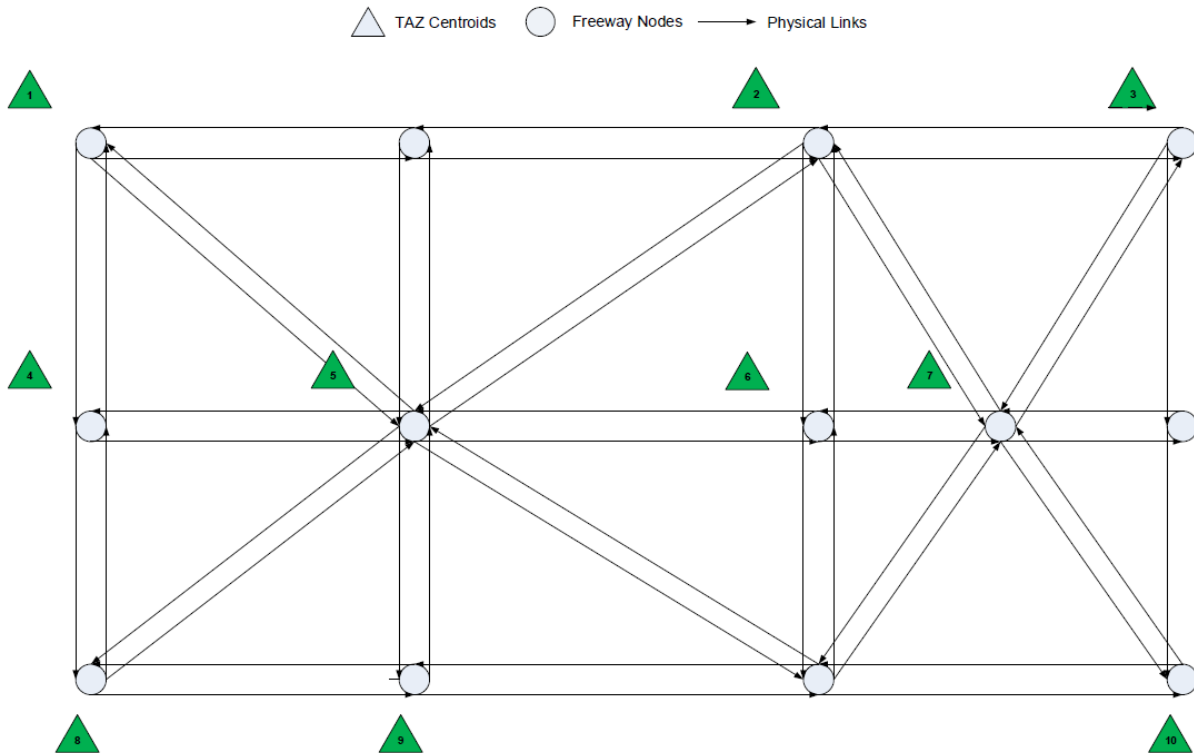


Figure 4: Example freeway network scheme

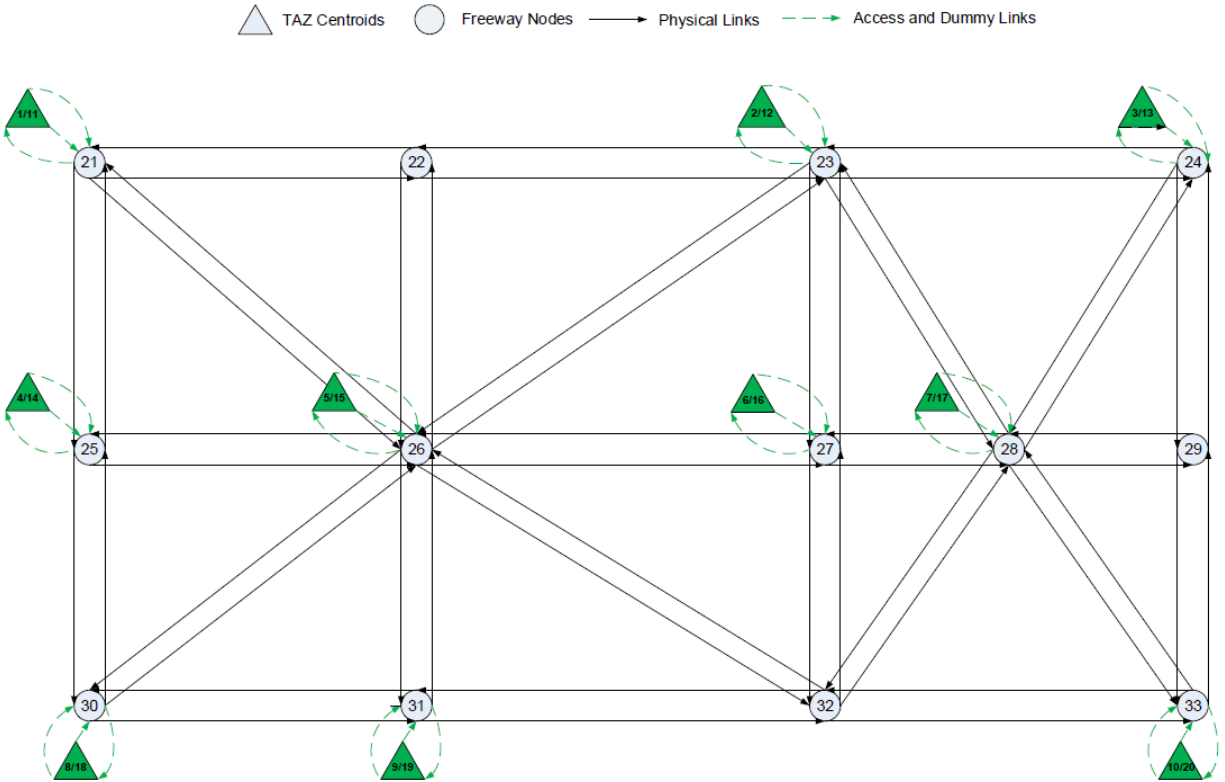


Figure 5: Example freeway network numbering in XXE

4.3.1.2 *XXE node-link input*

After properly numbering the freeway network, the node-link information may be added to the XXE Node-Link Data form, as shown in Figure 6 and Figure 7. In the node-link form, the property “Physical Link” should be set as “No” for access links and “Yes” for actual freeway links that are included in the analysis. Besides the node-link information, for each freeway link, the corresponding freeway facility settings should be also specified. This is done through the property “Freeway Facilities” in the node-link form, which will open the HCM-CALC FF module for freeway facility input, as shown in Figure 8. Note that access links are only needed for the purpose of XXE network topology, and they do not have any corresponding freeway facilities, and thus do not need to specify any facility input. The freeway facilities input for the example freeway network are specified as appropriate by the project, which include various segments, such as basic, on/off ramp, and weaving segments. To follow the rules of the HCM freeway facility core methodology, the freeway facilities are all start and end with basic segments and within the length of 12 miles. XXE can save the above data input into a freeway network base file.

Figure 6 displays two screenshots of the 'Node-Link Data' application, showing the input for links 1 to 42 in a freeway network. The application window title is 'Node-Link Data' and the status bar indicates 'First Physical Node 21 Total Nodes 33'.

The left screenshot shows links 1 to 21. The right screenshot shows links 22 to 42.

Link ID	From Node	To Node	Physical Link	Freeway Facilities	Volume-Travel Time Relationship
1	1	21	No	Open	Show
2	2	23	No	Open	Show
3	3	24	No	Open	Show
4	4	25	No	Open	Show
5	5	26	No	Open	Show
6	6	27	No	Open	Show
7	7	28	No	Open	Show
8	8	30	No	Open	Show
9	9	31	No	Open	Show
10	10	33	No	Open	Show
11	11	21	No	Open	Show
12	12	23	No	Open	Show
13	13	24	No	Open	Show
14	14	25	No	Open	Show
15	15	26	No	Open	Show
16	16	27	No	Open	Show
17	17	28	No	Open	Show
18	18	30	No	Open	Show
19	19	31	No	Open	Show
20	20	33	No	Open	Show
21	21	11	No	Open	Show
22	21	22	Yes	Open	Show
23	21	25	Yes	Open	Show
24	21	26	Yes	Open	Show
25	22	21	Yes	Open	Show
26	22	23	Yes	Open	Show
27	22	26	Yes	Open	Show
28	23	12	No	Open	Show
29	23	22	Yes	Open	Show
30	23	24	Yes	Open	Show
31	23	26	Yes	Open	Show
32	23	27	Yes	Open	Show
33	23	28	Yes	Open	Show
34	24	13	No	Open	Show
35	24	23	Yes	Open	Show
36	24	28	Yes	Open	Show
37	24	29	Yes	Open	Show
38	25	14	No	Open	Show
39	25	21	Yes	Open	Show
40	25	26	Yes	Open	Show
41	25	30	Yes	Open	Show
42	26	15	No	Open	Show

Figure 6: Example freeway network node-link input (link 1 to 42) in XXE

Figure 7 displays two screenshots of the 'Node-Link Data' application, showing the input for links 43 to 82 in a freeway network. The application window title is 'Node-Link Data' and the status bar indicates 'First Physical Node 21 Total Nodes 33'.

The left screenshot shows links 43 to 63. The right screenshot shows links 64 to 82. Link 64 is highlighted in blue in the right screenshot.

Link ID	From Node	To Node	Physical Link	Freeway Facilities	Volume-Travel Time Relationship
43	26	21	Yes	Open	Show
44	26	22	Yes	Open	Show
45	26	23	Yes	Open	Show
46	26	25	Yes	Open	Show
47	26	27	Yes	Open	Show
48	26	30	Yes	Open	Show
49	26	31	Yes	Open	Show
50	26	32	Yes	Open	Show
51	27	16	No	Open	Show
52	27	23	Yes	Open	Show
53	27	26	Yes	Open	Show
54	27	28	Yes	Open	Show
55	27	32	Yes	Open	Show
56	28	17	No	Open	Show
57	28	23	Yes	Open	Show
58	28	24	Yes	Open	Show
59	28	27	Yes	Open	Show
60	28	29	Yes	Open	Show
61	28	32	Yes	Open	Show
62	28	33	Yes	Open	Show
63	29	24	Yes	Open	Show
64	29	28	Yes	Open	Show
65	29	33	Yes	Open	Show
66	30	18	No	Open	Show
67	30	25	Yes	Open	Show
68	30	26	Yes	Open	Show
69	30	31	Yes	Open	Show
70	31	19	No	Open	Show
71	31	26	Yes	Open	Show
72	31	30	Yes	Open	Show
73	31	32	Yes	Open	Show
74	32	26	Yes	Open	Show
75	32	27	Yes	Open	Show
76	32	28	Yes	Open	Show
77	32	31	Yes	Open	Show
78	32	33	Yes	Open	Show
79	33	20	No	Open	Show
80	33	28	Yes	Open	Show
81	33	29	Yes	Open	Show
82	33	32	Yes	Open	Show

Figure 7: Example freeway network node-link input (link 43 to 82) in XXE

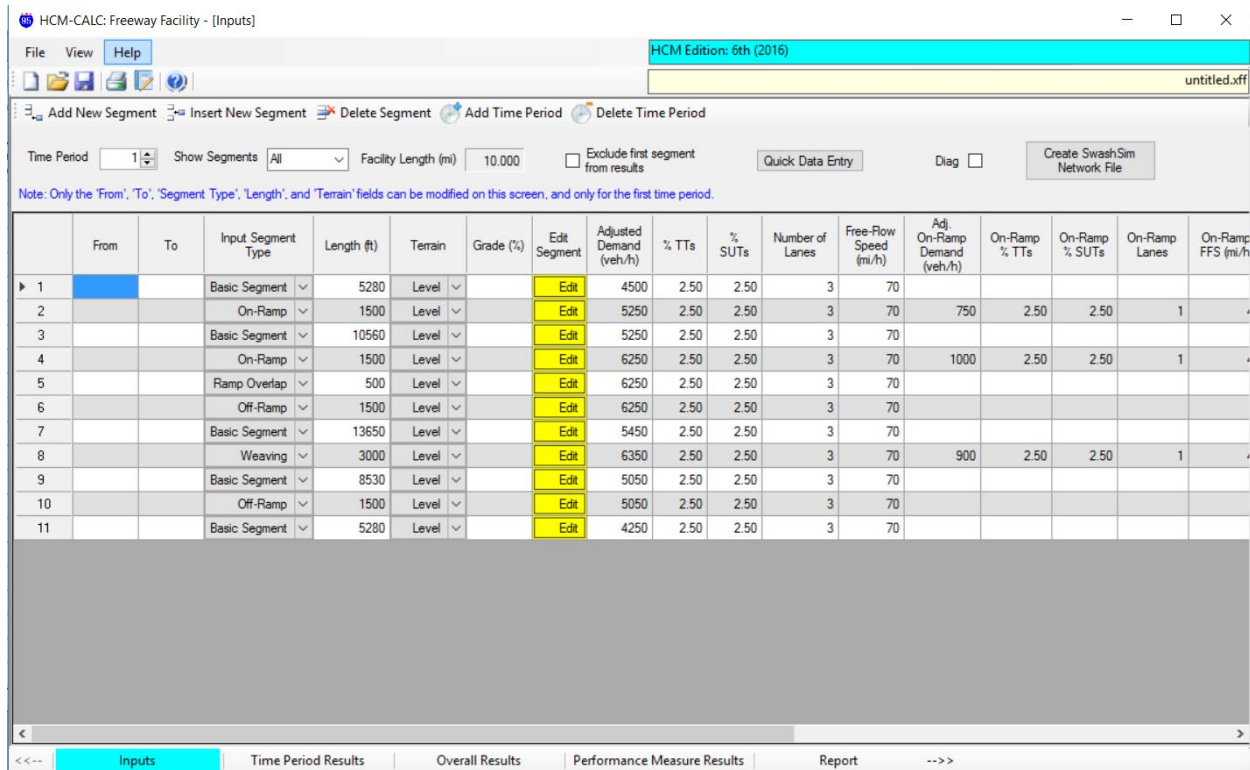


Figure 8: Freeway facility settings in HCM-CALC FF module

4.3.1.3 *XXE OD data input*

In addition to the freeway network node-link information, the OD data of the example freeway network is specified in the XXE Origin-Destination Data form, which include the TAZ centroids and associated trips for each OD pair of the freeway network, as shown in Figure 9 and Figure 10. XXE can save these data input into a freeway network OD data base file.

The figure shows two side-by-side windows titled "Origin-Destination Data". Each window contains a table with three columns: "Origin Zone", "Destination Zone", and "Number of Trips".

Entry	Origin Zone	Destination Zone	Number of Trips
1	1	2	1597
2	1	3	960
3	1	4	978
4	1	5	1945
5	1	6	840
6	1	7	1638
7	1	8	930
8	1	9	1176
9	1	10	1420
10	2	1	940
11	2	3	1428
12	2	4	849
13	2	5	1694
14	2	6	964
15	2	7	1743
16	2	8	849
17	2	9	994
18	2	10	1306
19	3	1	709
20	3	2	1845
21	3	4	1329
22	3	5	1640
23	3	6	1243
24	3	7	2418
25	3	8	1352
26	3	9	1865
27	3	10	895
28	4	1	918
29	4	2	1074
30	4	3	869
31	4	5	1297
32	4	6	966
33	4	7	835
34	4	8	1117
35	4	9	947
36	4	10	1246
37	5	1	2157
38	5	2	959
39	5	3	840
40	5	4	1296
41	5	6	968
42	5	7	736
43	5	8	956
44	5	9	1357
45	5	10	879
46	6	1	855

Figure 9: Example freeway network OD data input (entry 1 to 46) in XXE

Entry	Origin Zone	Destination Zone	Number of Trips
47	6	2	966
48	6	3	760
49	6	4	1378
50	6	5	841
51	6	7	849
52	6	8	1410
53	6	9	921
54	6	10	1379
55	7	1	1243
56	7	2	850
57	7	3	1654
58	7	4	803
59	7	5	996
60	7	6	2133
61	7	8	935
62	7	9	906
63	7	10	1858
64	8	1	718
65	8	2	788
66	8	3	908
67	8	4	1145
68	8	5	842
69	8	6	1356
70	8	7	665
71	8	9	785
72	8	10	1467
73	9	1	1947
74	9	2	1528
75	9	3	1225
76	9	4	785
77	9	5	1321
78	9	6	943
79	9	7	939
80	9	8	868
81	9	10	1824
82	10	1	915
83	10	2	1654
84	10	3	764
85	10	4	851
86	10	5	703
87	10	6	1534
88	10	7	2437
89	10	8	994
90	10	9	1698

Figure 10: Example freeway network OD data input (entry 47 to 90) in XXE

4.3.2 Freeway network TTR scenario generation

After the setup of freeway network base files in XXE, the HCM-CALC TTR/ATDM module can load the base files as the base freeway network (Figure 11) and then generate freeway network TTR scenarios, and assign scenario adjustment factors (DAF, CAF, and SAF) to the base freeway network.

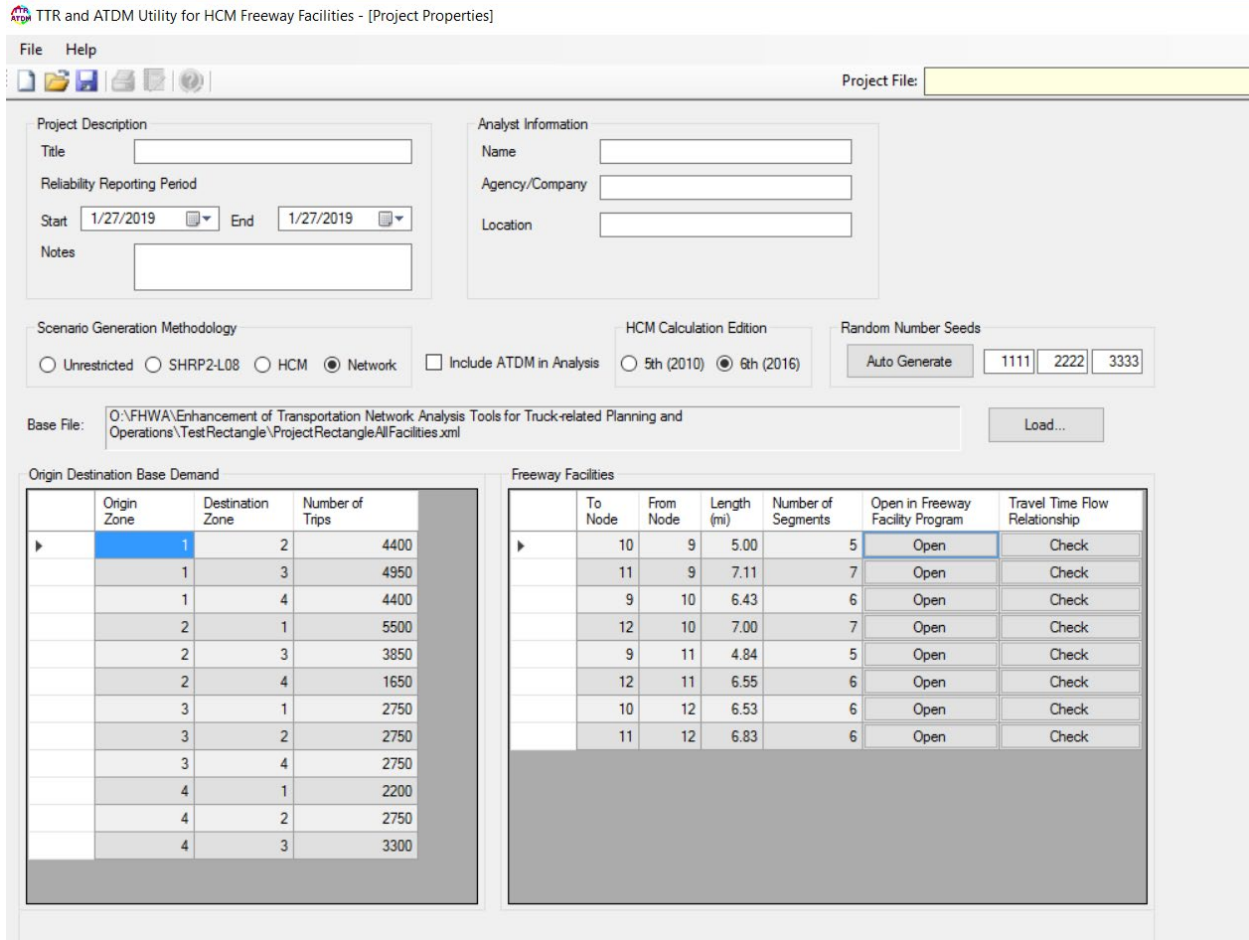


Figure 11: Freeway network base file loaded in HCM-CALC TTR/ATDM module

4.3.2.1 OD demand combinations

For each OD pair of the example freeway network, OD demand combination demand multipliers are specified. Then, HCM-CALC TTR/ATDM module generate scenarios based on the demand combinations and scenario replication number. DAF for each demand combination is calculated by HCM-CALC TTR/ATDM module and assigned to scenarios that are associated with the demand combination. Note that this process should be completed and saved for all OD pairs of the freeway network, Figure 12 shows the settings for one OD pair (zone 1 to zone 2).

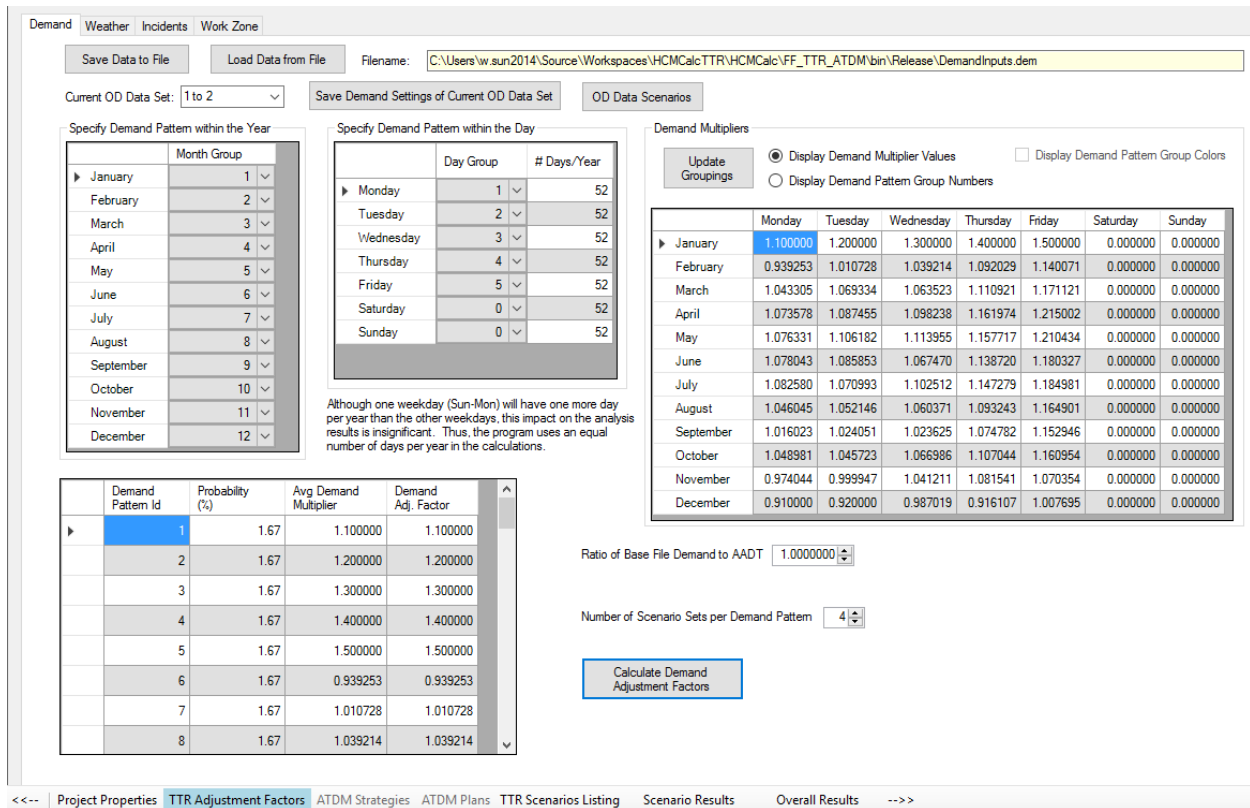


Figure 12: OD demand combinations input (zone 1 to zone 2) in HCM-CALC TTR/ATDM

4.3.2.2 Weather events

As shown in Figure 13, weather events settings, such as monthly weather probabilities, event duration and adjustment factors for the example freeway network are specified. HCM-CALC TTR/ATDM module can generate the list of weather events for the RRP (Figure 14), as well as weather events charts (weather event type distribution, weather event month distribution, and weather event start time distribution, etc.), as shown in Figure 15.

Demand Weather Incidents Work Zone

Save Data to File Load Data from File Filename: C:\Users\w_sun2014\Source\Workspaces\HCMCalc\TTR\HCMCalc\FF_TTR_ATDM\bin\Release\WeatherInputs.wea

Calculate Expected Weather Event Frequencies (1)

View Probabilities By

Base Probabilities by Month

Expected Weather Event Frequencies

List of Weather Events (2)

	Normal Weather	Medium Rain	Heavy Rain	Light Snow	Light-Med Snow	Med-Heavy Snow	Heavy Snow	Severe Cold	Low Visibility	Very Low Visibility	Minimum Visibility	Total
▶ January	95.722298	0.738000	0.502000	1.477000	0.213000	0.038000	0.000000	0.000000	0.784000	0.000000	0.525000	99.999
February	96.839203	1.040000	0.144000	0.544000	0.386000	0.000000	0.000000	0.000000	0.727000	0.000000	0.319000	99.999
March	97.414902	1.364000	0.670000	0.000000	0.000000	0.000000	0.000000	0.000000	0.242000	0.000000	0.308000	99.999
April	97.414902	1.364000	0.670000	0.000000	0.000000	0.000000	0.000000	0.000000	0.242000	0.000000	0.308000	99.999
May	97.511803	1.295000	1.086000	0.000000	0.000000	0.000000	0.000000	0.000000	0.108000	0.000000	0.000000	100.001
June	97.726402	0.936000	1.338000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	100.000
July	97.526299	0.865000	1.523000	0.000000	0.000000	0.000000	0.000000	0.000000	0.086000	0.000000	0.000000	100.000
August	98.121101	0.369000	1.141000	0.000000	0.000000	0.000000	0.000000	0.000000	0.369000	0.000000	0.000000	100.000
September	97.869797	1.075000	1.056000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	100.001
October	98.408096	0.486000	0.325000	0.000000	0.000000	0.000000	0.000000	0.000000	0.690000	0.000000	0.091000	100.000
November	97.936897	1.059000	0.709000	0.000000	0.000000	0.000000	0.000000	0.000000	0.294000	0.000000	0.000000	99.999
December	95.714500	0.614000	0.778000	0.695000	0.262000	0.069000	0.000000	0.000000	1.404000	0.000000	0.463000	100.000

	Normal Weather	Medium Rain	Heavy Rain	Light Snow	Light-Med Snow	Med-Heavy Snow	Heavy Snow	Severe Cold	Low Visibility	Very Low Visibility	Minimum Visibility
▶ Average Duration for Weather Type (min)	0.00	40.22	33.69	93.09	33.35	21.66	7.30	0.00	76.17	0.00	144.88
Default Capacity Adjustment Factor (%)	100.00	92.76	85.87	95.71	91.34	88.96	77.57	91.55	90.33	88.33	89.51
Default FFS Adjustment Factor (%)	100.00	95.00	93.00	92.00	90.00	88.00	86.00	95.00	95.00	94.00	94.00
Demand Adjustment Factor (%)	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

<-- Project Properties TTR Adjustment Factors ATDM Strategies ATDM Plans TTR Scenarios Listing Scenario Results Overall Results -->

Figure 13: Weather events settings in HCM-CALC

List of Weather Events (HCM)

Weather Events Charts

Weather Event #	Associated Month in RRP	Weather Event	Assigned Scenario #	Start Time Period	Duration in TP's	DAF	SAF	CAF	
1	January	Medium Rain	3		10	3	1.00	0.95	0.93
2	January	Heavy Rain	7		9	2	1.00	0.93	0.86
3	January	Light Snow	17		6	6	1.00	0.92	0.96
4	February	Medium Rain	34		10	3	1.00	0.95	0.93
5	March	Medium Rain	49		12	3	1.00	0.95	0.93
6	March	Heavy Rain	56		11	2	1.00	0.93	0.86
7	April	Medium Rain	68		6	3	1.00	0.95	0.93
8	April	Heavy Rain	74		11	2	1.00	0.93	0.86
9	May	Medium Rain	98		10	3	1.00	0.95	0.93
10	May	Heavy Rain	96		6	2	1.00	0.93	0.86
11	June	Medium Rain	109		6	3	1.00	0.95	0.93
12	June	Heavy Rain	116		2	2	1.00	0.93	0.86
13	June	Heavy Rain	112		2	2	1.00	0.93	0.86
14	July	Medium Rain	123		1	3	1.00	0.95	0.93
15	July	Heavy Rain	129		11	2	1.00	0.93	0.86
16	July	Heavy Rain	127		2	2	1.00	0.93	0.86
17	August	Heavy Rain	142		11	2	1.00	0.93	0.86
18	September	Medium Rain	172		11	3	1.00	0.95	0.93
19	September	Heavy Rain	167		7	2	1.00	0.93	0.86
20	November	Medium Rain	213		10	3	1.00	0.95	0.93
21	November	Heavy Rain	209		5	2	1.00	0.93	0.86
22	December	Heavy Rain	236		12	2	1.00	0.93	0.86
23	December	Low Visibility	234		3	5	1.00	0.95	0.90

Figure 14: List of weather events generated in HCM-CALC

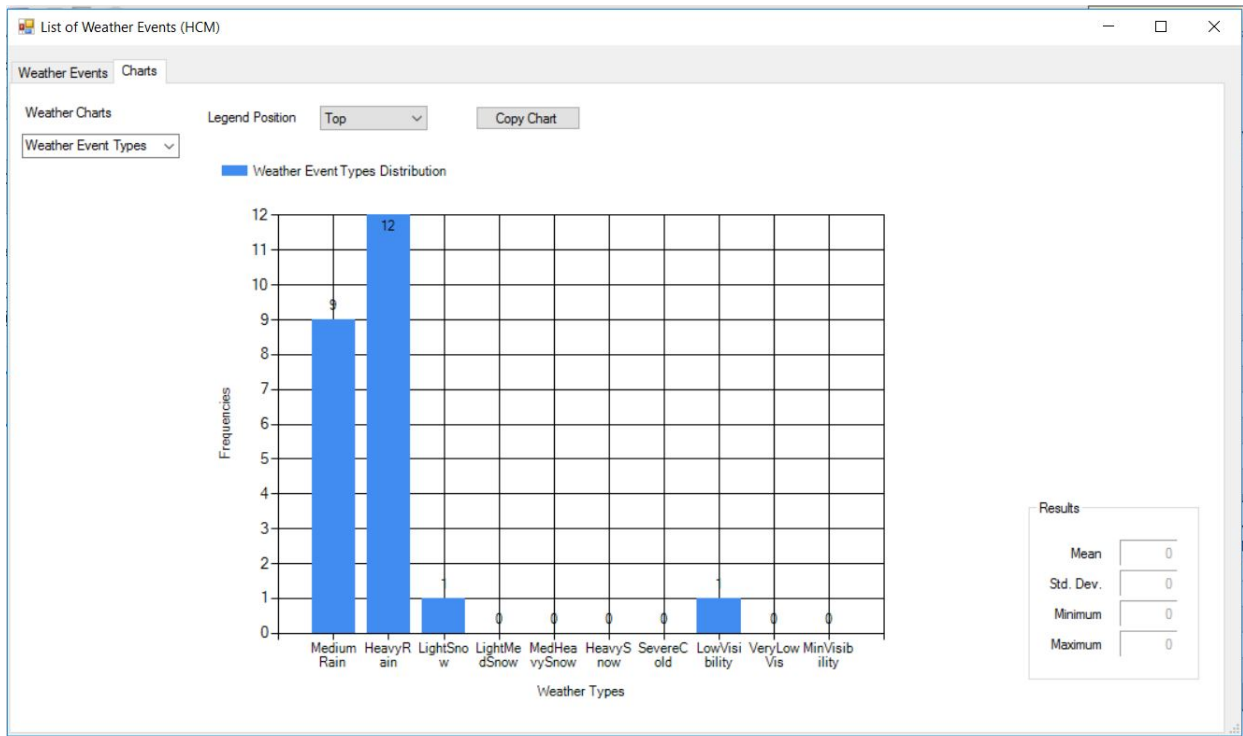


Figure 15: Weather events charts in HCM-CALC

4.3.2.3 Incident events

For each facility in the example freeway network, incident events settings, such as monthly incident rates and distribution probability of each incident type, and incident type settings, such as duration and adjustment factors, are specified. Note that incident events settings and incident type settings need to be specified and saved for each freeway facilities in the network, and Figure 16 shows the specific settings for one freeway facility (freeway node 9 to 10). Then, HCM-CALC TTR/ATDM module can generate the list of incident events (Figure 17) and incident events charts (incident severity distribution, incident event month distribution, incident start time distribution, and incident location distribution, etc.) for the current freeway facility, as shown in Figure 18.

Demand Weather Incidents Work Zone

Open Incident Adjustment Factors Save Data to File Load Data from File Filename: C:\Users\w.sun2014\Source\Workspaces\HCMCalcTTR\HCMCalc\FF_TTR_ATDM\bin\Release\IncidentInputs.inc

Current Facility: Node 9 to Node 10 Save Incident Settings of Current Facility

Incident Frequency Calculation Method
 Incident Rates Crash Rates HERS Model Direct Entry

Crash to Incident Rate Ratio: 7.0
 % of AADT in Study Period: 33.84
 Calculate Crash Rates with HERS Model

Calculate Incident Frequencies

List of Incident Events

Month	IncidentFrequencies
January	0.7051
February	0.7051
March	0.7051
April	0.7051
May	0.7051
June	0.7051
July	0.7051
August	0.7051
September	0.7051
October	0.7051
November	0.7051
December	0.7051

Monthly Incident Rates (Incidents/100 million VMT)

Month	Rate
January	1050
February	1050
March	1050
April	1050
May	1050
June	1050
July	1050
August	1050
September	1050
October	1050
November	1050
December	1050

Incident Durations

	Incident Type Distribution	Expected Duration (min)	Std. Dev. of Duration (min)	Minimum Duration (min)	Maximum Duration (min)
Shoulder Closure	0.75	32.00	15.00	8.70	58.00
One Lane Closure	0.20	34.00	14.00	16.00	58.20
Two Lane Closure	0.05	53.00	14.00	30.50	66.90
Three Lane Closure	0.00	69.00	22.00	36.00	93.30
Four Lane Closure	0.00	69.00	22.00	36.00	93.30

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Figure 16: Incident event input in the HCM-CALC

List of Incident Events (HCM)

Incident #	Scenario #	Severity Type	Start Time Period	Duration in TP's	Location Segment #	DAF	SAF	CAF	
1	9	TwoLaneClosure		7	4	10	1.000	1.000	0.170
2	19	TwoLaneClosure		8	3	6	1.000	1.000	0.170
3	10	OneLaneClosure		5	2	11	1.000	1.000	0.490
4	4	TwoLaneClosure		12	4	7	1.000	1.000	0.170
5	8	ShoulderClosure		8	2	6	1.000	1.000	0.830
6	7	OneLaneClosure		3	2	1	1.000	1.000	0.490
7	14	OneLaneClosure		10	2	1	1.000	1.000	0.490
8	6	ShoulderClosure		7	2	7	1.000	1.000	0.830
9	6	TwoLaneClosure		9	3	8	1.000	1.000	0.170
10	16	OneLaneClosure		7	4	6	1.000	1.000	0.490
11	16	ShoulderClosure		12	2	5	1.000	1.000	0.830
12	11	TwoLaneClosure		2	4	3	1.000	1.000	0.170
13	11	OneLaneClosure		3	2	9	1.000	1.000	0.490
14	15	TwoLaneClosure		11	3	7	1.000	1.000	0.170
15	15	OneLaneClosure		1	2	4	1.000	1.000	0.490
16	13	TwoLaneClosure		10	4	8	1.000	1.000	0.170
17	13	OneLaneClosure		3	1	11	1.000	1.000	0.490
18	13	TwoLaneClosure		9	4	7	1.000	1.000	0.170
19	28	TwoLaneClosure		3	3	10	1.000	1.000	0.170
20	32	TwoLaneClosure		9	3	8	1.000	1.000	0.170
21	29	ShoulderClosure		8	2	6	1.000	1.000	0.830
22	27	OneLaneClosure		8	1	1	1.000	1.000	0.490
23	21	ShoulderClosure		5	1	11	1.000	1.000	0.830
24	25	OneLaneClosure		3	1	1	1.000	1.000	0.490

Figure 17: List of incident events of a specific freeway facility in HCM-CALC

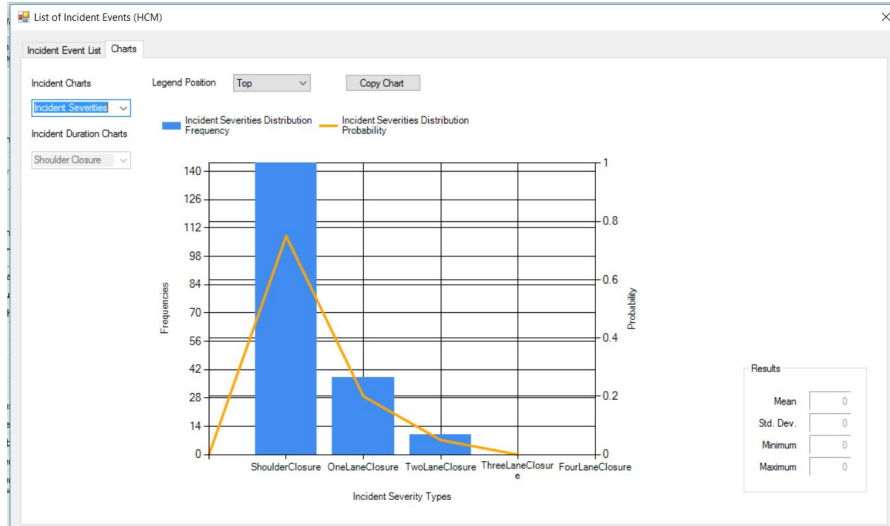


Figure 18: Incident events chart in HCM-CALC

4.3.2.4 *Work zone events*

The scheduled work zone events of the example freeway network are specified in the HCM-CALC, as shown in Figure 19, work zone input should be specified and saved for each facility that contains work zone schedule in the freeway network. HCM-CALC TTR/ATDM module can generate the list of work zone events and assign them to scenarios, as shown in Figure 20.

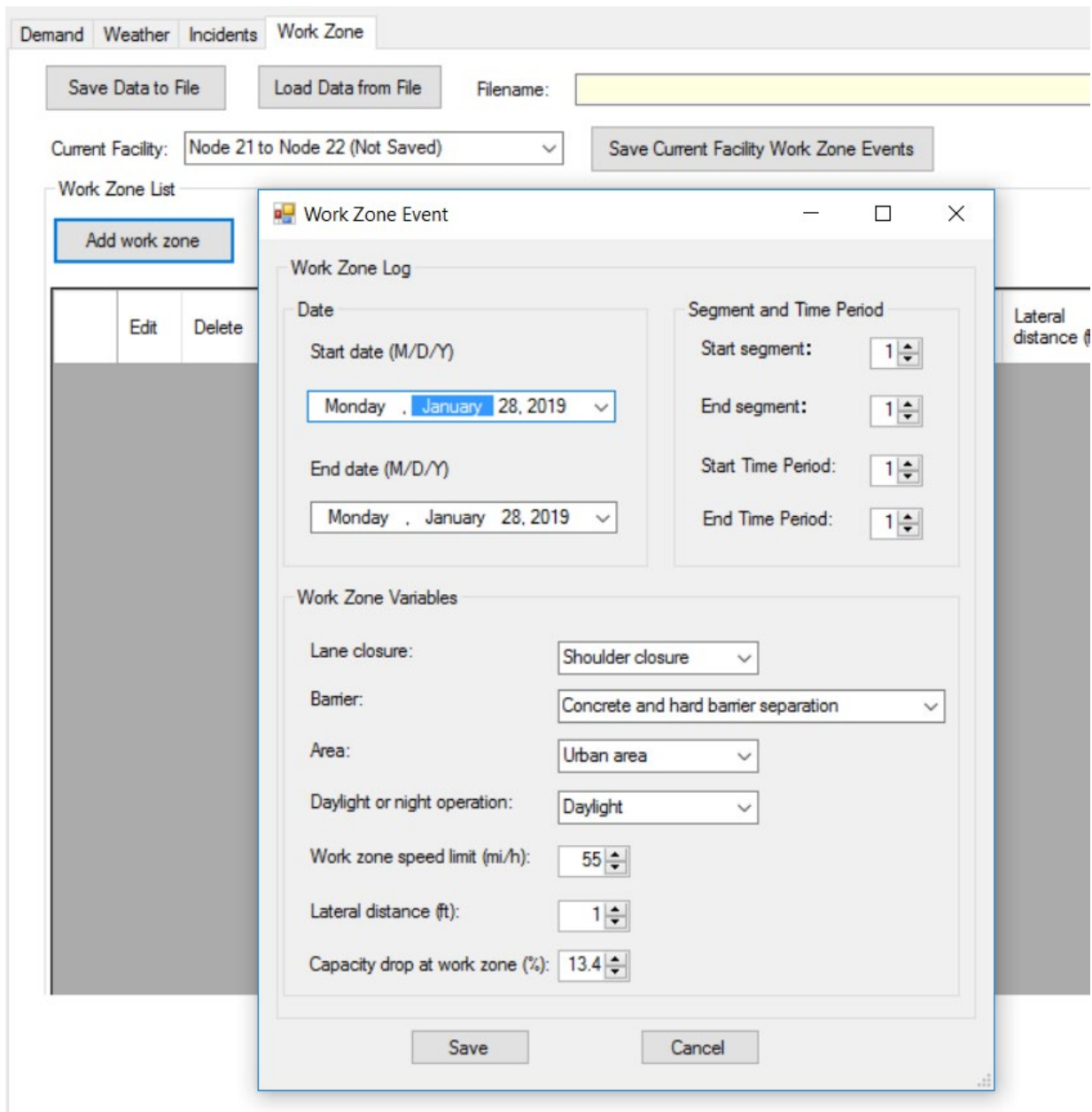


Figure 19: Work zone input in HCM-CALC

The screenshot shows the 'Work Zone List' table in the HCM-CALC software. The table has 15 columns: Edit, Delete, Lane closure, Speed limit (mi/h), Barrier, Area, Day/night operation, Lateral distance (ft), Start date, End date, Start segment, End segment, Start time period, End time period, and Adjustment factors. There are three rows of data, each with an 'Edit' and 'Delete' button in the first two columns. The 'Adjustment factors' column has a 'Load' button for each row.

Edit	Delete	Lane closure	Speed limit (mi/h)	Barrier	Area	Day/night operation	Lateral distance (ft)	Start date	End date	Start segment	End segment	Start time period	End time period	Adjustment factors
Edit	Delete	OneLaneClosure	50	PlasticAndSoft	Urban	Daylight	1	1/16/2019	1/18/2019	4	8	3	8	Load
Edit	Delete	OneLaneClosure	55	ConcreteAndHard	Rural	Daylight	1	3/6/2019	3/14/2019	6	8	4	12	Load
Edit	Delete	TwoLaneClosure	45	ConcreteAndHard	Urban	Daylight	1	5/22/2019	5/24/2019	4	4	1	10	Load

Figure 20: List of work zone events for a specific freeway facility in HCM-CALC

4.3.2.5 Scenario list

After the assignment of OD demand patterns, weather events, incident events, and work zone events for the example freeway network, HCM-CALC generates the list of network scenarios, as shown in Figure 21.

Scenario Number	Probability	Month	Day	OD Set	Weather Events	Incident Events	Work Zone Events	Freeway Facilities	Traffic Assignment
1	0.004	January	Monday	Show	Normal Weather	Show	Show	Show	Run
2	0.004	January	Monday	Show	Normal Weather	Show	Show	Show	Run
3	0.004	January	Monday	Show	1 Weather Event	Show	Show	Show	Run
4	0.004	January	Monday	Show	Normal Weather	Show	Show	Show	Run
5	0.004	January	Tuesday	Show	Normal Weather	Show	Show	Show	Run
6	0.004	January	Tuesday	Show	Normal Weather	Show	Show	Show	Run
7	0.004	January	Tuesday	Show	1 Weather Event	Show	Show	Show	Run
8	0.004	January	Tuesday	Show	Normal Weather	Show	Show	Show	Run
9	0.004	January	Wednesday	Show	Normal Weather	Show	Show	Show	Run
10	0.004	January	Wednesday	Show	Normal Weather	Show	Show	Show	Run
11	0.004	January	Wednesday	Show	Normal Weather	Show	Show	Show	Run
12	0.004	January	Wednesday	Show	Normal Weather	Show	Show	Show	Run
13	0.004	January	Thursday	Show	Normal Weather	Show	Show	Show	Run
14	0.004	January	Thursday	Show	Normal Weather	Show	Show	Show	Run
15	0.004	January	Thursday	Show	Normal Weather	Show	Show	Show	Run
16	0.004	January	Thursday	Show	Normal Weather	Show	Show	Show	Run
17	0.004	January	Friday	Show	1 Weather Event	Show	Show	Show	Run
18	0.004	January	Friday	Show	Normal Weather	Show	Show	Show	Run
19	0.004	January	Friday	Show	Normal Weather	Show	Show	Show	Run
20	0.004	January	Friday	Show	Normal Weather	Show	Show	Show	Run
21	0.004	February	Monday	Show	Normal Weather	Show	Show	Show	Run
22	0.004	February	Monday	Show	Normal Weather	Show	Show	Show	Run
23	0.004	February	Monday	Show	Normal Weather	Show	Show	Show	Run
24	0.004	February	Monday	Show	Normal Weather	Show	Show	Show	Run
25	0.004	February	Tuesday	Show	Normal Weather	Show	Show	Show	Run
26	0.004	February	Tuesday	Show	Normal Weather	Show	Show	Show	Run
27	0.004	February	Tuesday	Show	Normal Weather	Show	Show	Show	Run

Figure 21: List of network scenarios generated in HCM-CALC

4.3.3 TTR scenario analysis

After scenario generation, HCM-CALC TTR/ATDM module can run analysis of all the scenarios of the example freeway network. For each scenario, the TTR/ATDM module performs the UE traffic assignment by calling the XXE with the scenario adjusted freeway facilities network file as input. The TTR/ATDM module should also aggregate the traffic assignment results obtained from XXE for each scenario into TTR performance measures.

4.3.3.1 Analysis settings

Before running analysis for all scenarios, analysis settings are specified, as shown in Figure 22. The analysis settings include the convergence criteria value and maximum number of iteration for the UE traffic assignment. Besides, a folder need to be specified to save the scenario results, this way, the results of each scenario can be saved into xml. files on the computer, instead of continuously consuming the computer memory while running the analysis. The initial implementation found that when the network is large enough, the accumulation of scenario results saved in the memory could eventually exceed the limit of computer memory, when it happens, the computer will use disk to run the software, which is very slow. In this case, the function is added for users to select a folder to save the

scenario results during the analysis, and once the analysis is completed for all scenarios, the results can be loaded into the TTR/ATDM module as needed.

Figure 23 shows the process bar when TTR/ATDM module runs scenario analysis. During this process, the TTR/ATDM module calls XXE to perform UE traffic assignment for each scenario.

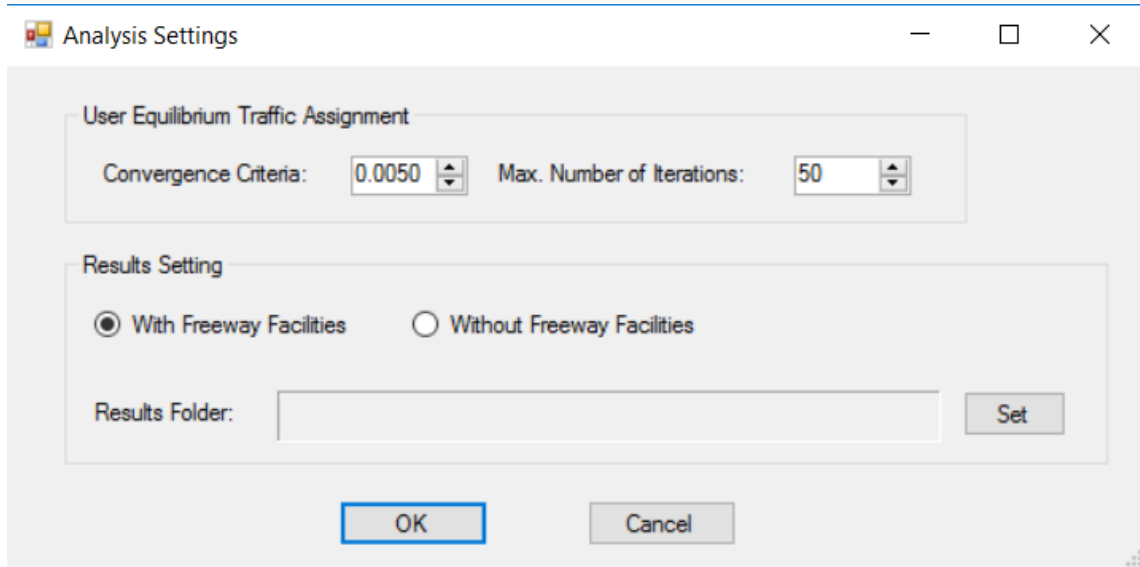


Figure 22: Analysis settings in HCM-CALC

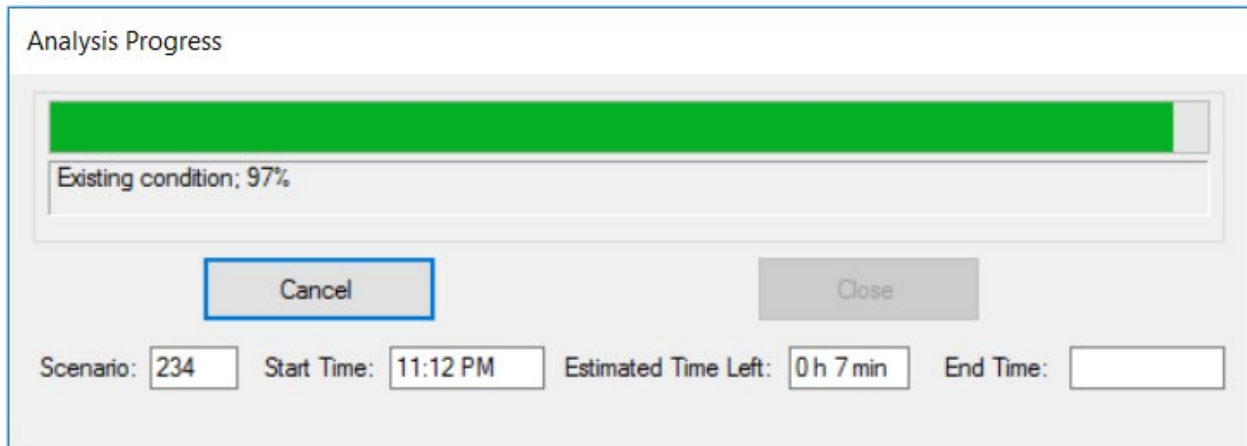


Figure 23: Run scenario analysis in HCM-CALC

4.3.3.1 Scenario results

The TTR/ATDM module obtains UE traffic assignment results of each scenario from the XXE and summarizes them into a list of scenario results, as shown in Figure 24.

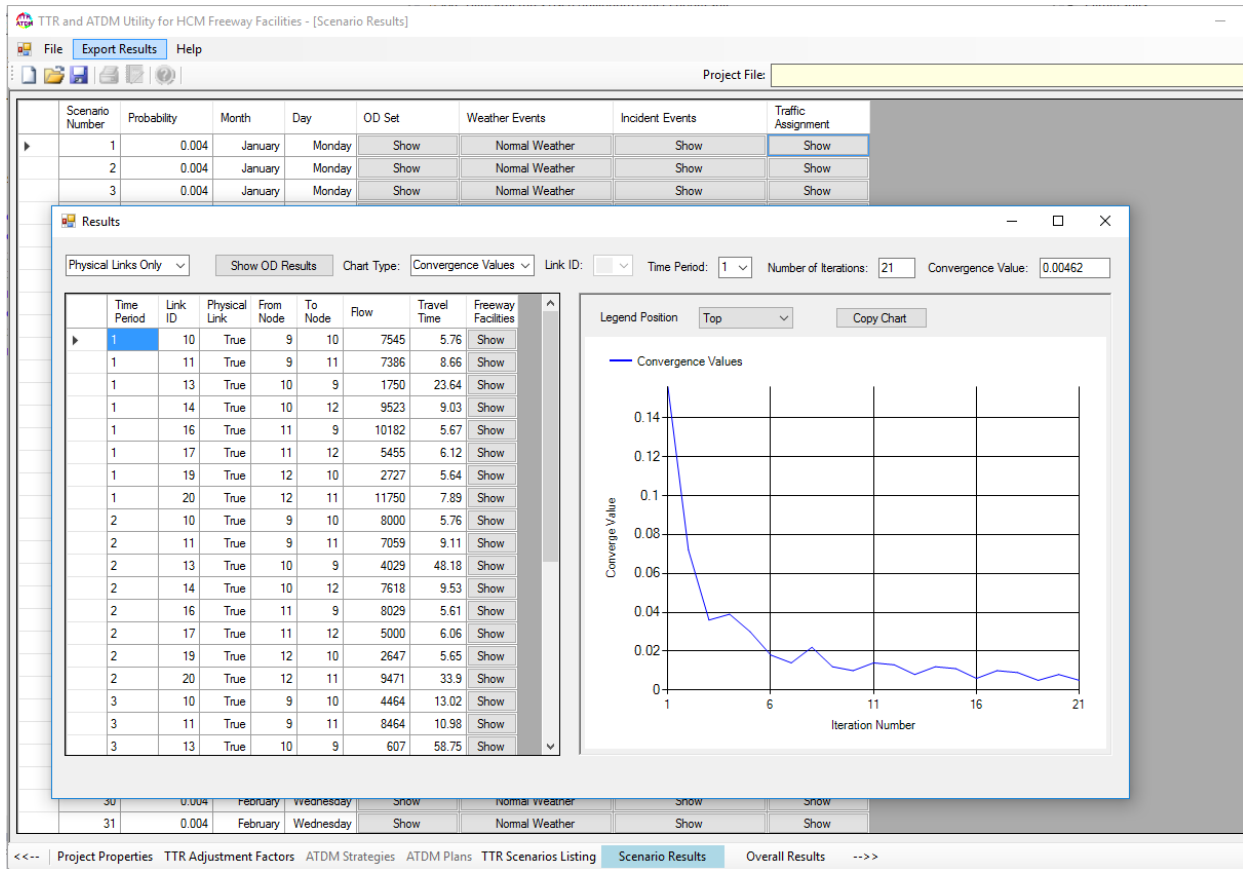


Figure 24: List of scenario results

4.3.3.2 Overall TTR results

The TTR/ATDM module aggregates traffic assignment results of each scenario to calculate TTR performance measures at three levels: network level, facility level, and OD level, as shown in Figure 25, Figure 26, and Figure 27, respectively.

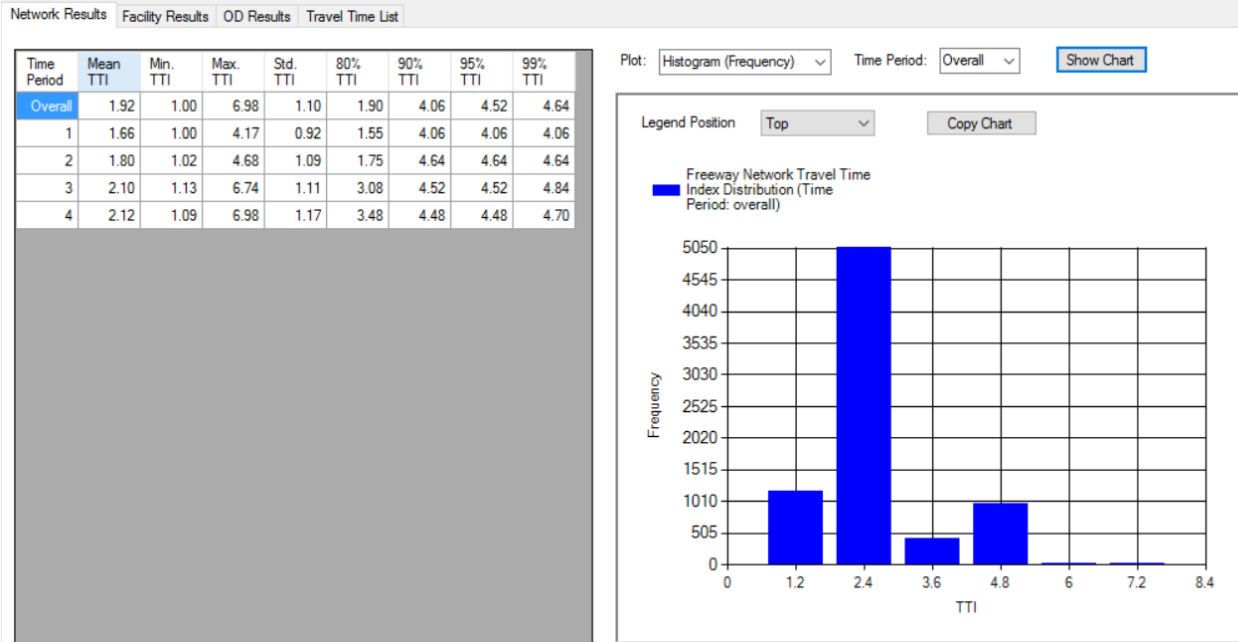


Figure 25: Network level TTR performance measures in HCM-CALC

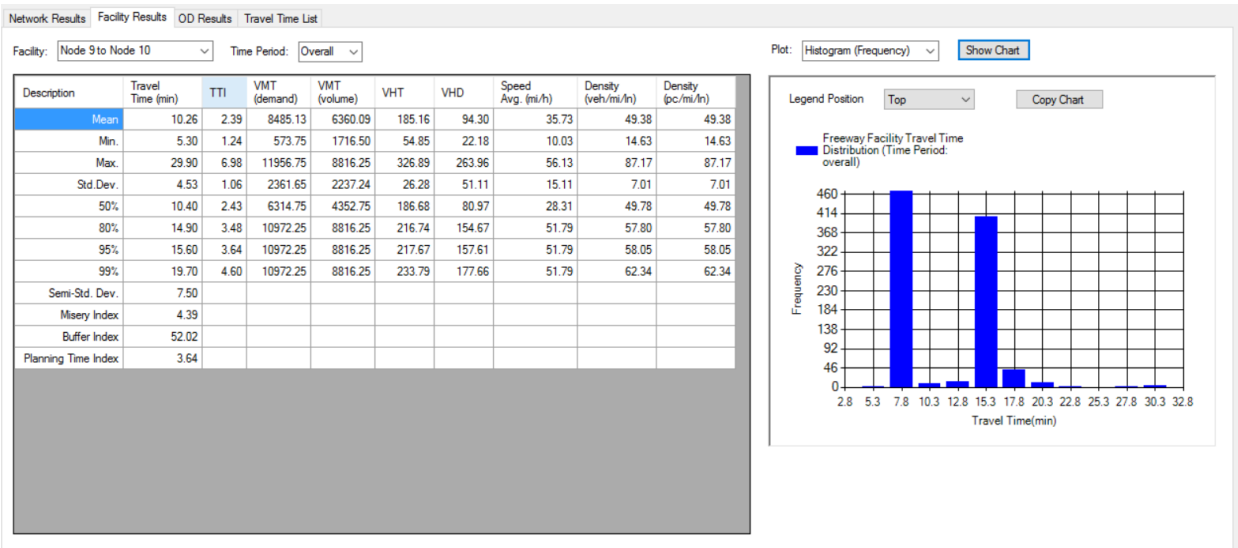


Figure 26: Facility level TTR performances in HCM-CALC

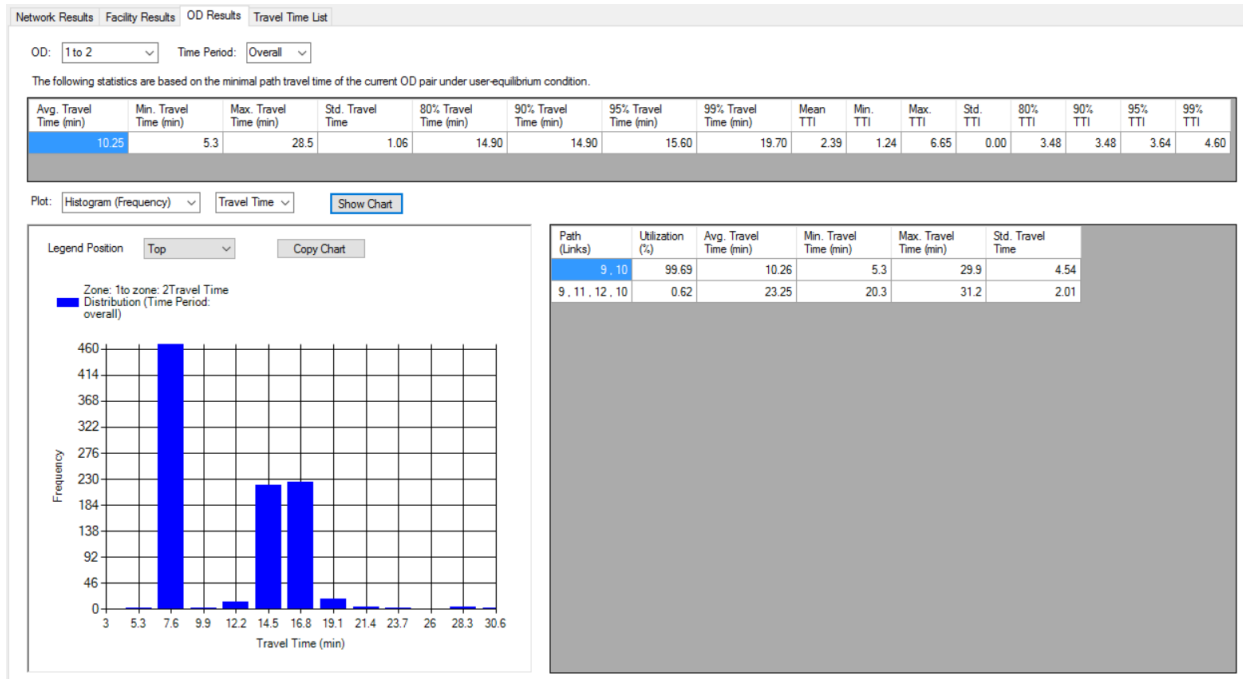


Figure 27: OD level TTR performance measures in HCM-CALC

4.3.3.1 Run time

The computer run time for a scenario analysis is proportional to the size of the freeway network and other settings as well, such as the UE traffic assignment convergence criteria and maximum number of iterations. For this example freeway network TTR analysis implementation, the computer run time was approximately 9 hours and 30 minutes for the analysis of all 240 scenarios. Note that this time did not include the time to set up freeway network base files and the TTR scenario generation. The specifications of the computer used to run the analysis were as follows:

- CPU: Intel Core i7-6700, 3.40 GHz
- RAM: 16.0 GB
- Operating System: Windows 10

These computer specifications are considered moderate by today's desktop computer technology standards. A top-level desktop computer, especially in another 1-2 years would likely run this same analysis in no more than half the time.

5.0 CONCLUSION

5.1 OVERVIEW

This project extends the HCM freeway TTR analysis methodology to the network level by integrating it with the UE traffic assignment methodology. As most network analysis uses simple link performance functions to represent the travel time and flow rate relationship, this project applies the HCM freeway facility core methodology, which can better represent freeway facility traffic conditions. Furthermore, the use of HCM freeway facility core methodology makes the proposed methodology more sensitive to the impacts of tracks through multivariate influences on PCE and more flexibility with lane configurations (e.g., managed lanes).

In addition, as the freeway network TTR analysis methodology is data and computationally intensive, this project developed a software tool, based on the modification and integration of two existing software programs: XXE (Washburn and Mannering, 2007) and HCM-CALC (Washburn, 2015), that can be used to apply the Facility TTR analysis methodology. This project also demonstrated an example implementation of the freeway network TTR analysis through the software tool. . The software tool provides a convenient and efficient approach for transportation planners and researchers to conduct the freeway network TTR analysis methodology, which helps to bridge the gap between research and practice.

5.2 CURRENT LIMITATIONS

5.2.1 HCM freeway facility TTR analysis methodology

Because the proposed freeway network TTR analysis methodology is based on the extension of the HCM freeway facility TTR analysis methodology, it inherits the facility TTR methodology's limitations. The key to the TTR analysis methodology is to generate scenarios that can represent the impacts of traffic demand variations, weather events, incident events, and work zone events occurred during the RRP on freeway facilities, which are affected by the limitations of the methodology in the following two aspects.

First, limitations that affects the methodology's ability to generate scenarios that match the field data. For example, the methodology assumes that incident events and traffic demand are independent of weather events. Even though the methodology generates scenarios on a calendar basis, which in some aspects already ties the traffic demand, incident events, weather events with each other. However, for instance, the occurrence of incident events are often directly caused by severe weather conditions and this correlation is not considered by the methodology. In addition, the methodology does not include full facility closures and weather events with small capacity reduction effects.

Second, limitations that affects the methodology's ability to reflect the impacts of the scenarios on the freeway facilities. The methodology uses adjustment factors, such as DAF, CAF, and SAF, to adjust the freeway facility conditions based on the scenarios. However, there are a few assumptions on the adjustment factors that still need to be tested. For instance, the methodology assumes that the effect of two or more CAFs or SAFs is multiplicative, and the DAF has a proportional effect across the entire facility.

5.2.2 Freeway facility spatial limit

Since the HCM freeway facility core methodology requires that the length of the freeway facility should be less than the distance a vehicle traveling with the average speed can achieve in 15 min, which is around 9 to 12 miles. In this case, during the freeway network setup, links that are longer than the spatial limit need to be divided into several links. This will introduce more links, and thus increase the UE traffic assignment calculation time.

5.2.3 Freeway facility starts with basic segment

The HCM freeway facility core methodology requires that the facility should start and end with basic segments. However, in reality, the links/freeway facilities within a network always start with on-ramp segments and end with off-ramp segments.

5.2.4 LOS F not allowed in the first and last time period/segment

The HCM freeway facility core methodology requires that the first and last time periods and segments should not operate at LOS F. However, when it comes to TTR analysis with so many scenarios, the requirements could be violated, and once it happens, the methodology can only provide limited results.

5.2.5 MSA approach

This project applies the MSA approach to solve the UE traffic assignment for the freeway network. However, the MSA approach has some well-known limitations on convergence. Since the MSA approach uses predetermined step sizes, this could lead to slow convergence and difficulty to define convergence criteria (Powell and Sheffi, 1982). In addition, the convergence problems could get worse when the traffic congestion level increases or with a large network (Sbayti et al., 2007).

5.3 RECOMMENDATIONS FOR FURTHER RESEARCH

5.3.1 Freeway facility TTR analysis methodology

Since the proposed freeway network TTR analysis methodology is based on the extension of the facility level methodology, further research is needed to improve the facility TTR analysis methodology's current limitations regarding the scenario generation and assignment process.

5.3.2 HCM freeway facility core methodology

As mentioned above, the HCM freeway facility core methodology has several limitations that may affect either the efficiency or the accuracy of the network level analysis. Future research should study the limitations of the HCM freeway facility core methodology and improve the methodology so that it can be better incorporated into the freeway network TTR analysis methodology.

5.3.3 Network traffic assignment

This project uses the MSA approach to solve the UE traffic assignment—further research could study the MSA approach when integrating with the HCM freeway facility core methodology and handle the slow convergence problem mentioned above. A better approach to solve the UE traffic

assignment should also be studied. In addition, future research could apply other network assignment methods than the UE traffic assignment, by calibrating with field data.

5.3.4 Software efficiency

Since software is the only feasible option to conduct the freeway network TTR analysis methodology, the efficiency of the software plays an important role to the feasibility of the methodology implementation by transportation researchers and practitioners. This project was focused primarily on the development of a network-level TTR analysis framework and implementation into a software prototype platform, not on computational efficiency. Nonetheless, the software tool developed as part of this project is written in a state-of-the-art programming language, C#. As such, it offers computational efficiencies over some older programming languages and alternative programming architectures, such as languages that do not compile into run-time binaries (e.g., Visual Basic for Applications in Microsoft Excel). However, there are undoubtedly some enhancements that could be made to the algorithms written for this project that will result in decreased run times. Future research could focus on improving the computational efficiency of the software tool through revising the code structure and data structures used in the various algorithms that comprise this analysis framework.

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