Modeling for Local Impact Analysis

December 2018

A Research Report from the National Center for Sustainable Transportation

Petros Ioannou, University of Southern California

National Center for Sustainable Transportation

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EXECUTIVE SUMMARY

The Los Angeles/Long Beach area is important for freight as it involves the twin ports and warehouses and freight hubs. The way freight is consolidated and distributed affects what is going on within the terminals and roadway and rail networks. The complexity and dynamics of the multimodal transportation networks in Los Angeles/Long Beach region that are also shared by passengers, together with the unpredictability of the effect of incidents, disruptions and demand, in temporal and special coordinates makes the local impact analysis of freight transportation a very challenging task despite recent advances in information technologies.

Under this project we developed a set of traffic simulation models for the Los Angeles/Long Beach region that allow us to evaluate the impact of new traffic flow control systems, vehicle routing, policy interventions such as land use changes and other ITS technologies on the efficiency of the transportation system and on the environment. The developed simulation models include: macroscopic simulation model for studying and evaluating large traffic networks, and microscopic simulation model for smaller networks. The macroscopic model focusses on flows and covers a much larger area as it is computationally much more efficient than the microscopic one. The microscopic model models the motion of each truck and vehicle, traffic lights, stop signs, speed limits, traffic rules etc. and resembles the real situation as close as possible.

The developed simulation models have been used to evaluate different systems and application scenarios, including freight priority traffic signal control, multimodal freight routing and the impact analysis of the spatial pattern changes of warehousing and distribution.

Introduction

Background & Motivation

Efficient freight movement is an essential factor not only in traffic efficiency but also in regional social development as well as in environmental considerations [1-3]. The growth of worldwide trade will increase traffic congestion and air pollution in metropolitan areas such as Los Angeles/Long Beach port region where there is a high concentration of both freight and passenger traffic that share the same infrastructure. The non-homogeneity between different classes of vehicles, i.e., passenger vehicles and trucks, limited capacity and high demand has a detrimental impact on overall transportation system efficiency. This situation becomes even worse during incidents and disruptions that change the network characteristics including road/rail closures that require rapid response and distribution of freight traffic across the multimodal network. It also makes the analysis of the impact of new traffic control technologies as well as the impact of policy interventions or of land use changes challenging.

The availability of fast computers and software tools opens the way for new approaches which can overcome the today's limitations of network modeling complexity. The traffic flow dynamical characteristics can be better understood and predicted using simulation models that are more complex and can capture phenomena that cannot be described by simple mathematical models [4]. These simulation models can also be integrated with control and optimization techniques to provide better and more robust decisions for complex and large scale systems. As a result, computer simulation models could be used to evaluate new traffic control approaches and investigate the impact of policy interventions before actual implementation saving time and cost as well as avoiding possible disruptions in the network.

In this project we developed a traffic simulation test bed that consists of different models for the Los Angeles/Long Beach region. The traffic simulation models include the macroscopic simulation model for the regional flow analysis, and the microscopic simulation model for smaller network areas but finer granularity. The macroscopic model focusses on flows and can be used to model flows in very large networks as it is computationally much more efficient than the microscopic one. The microscopic model simulates the motion of each truck and vehicle, takes into account traffic lights, stop signs, speed limits, traffic rules etc. and resembles the real situation as close as it gets. The simulation test bed is used to evaluate the impact of different systems, which have an effect on freight movements and traffic volumes on the port terminals and adjacent traffic networks. These application examples include the freight priority traffic signal control, Co- Simulation Optimization control, impact analysis of warehousing and distribution dynamics.

Structure of Report

The following sections are organized as follows: Section of Simulation Testbed Development presents the simulation models developed in the project. The section on the Co-Simulation Optimization Control Approach demonstrates the use of the developed simulation models for freight load balancing via optimum routing in a multimodal environment. Section of application examples describes the experiments realized and presents the results using the testbed models. Section of Conclusion concludes with the summary of project.

Simulation Testbed

Figure 1 shows the main components of the simulation test bed which is a suite of different simulation models interacting with each other by capturing in addition to individual dynamics the interactions between different modes, terminals, warehouses etc.

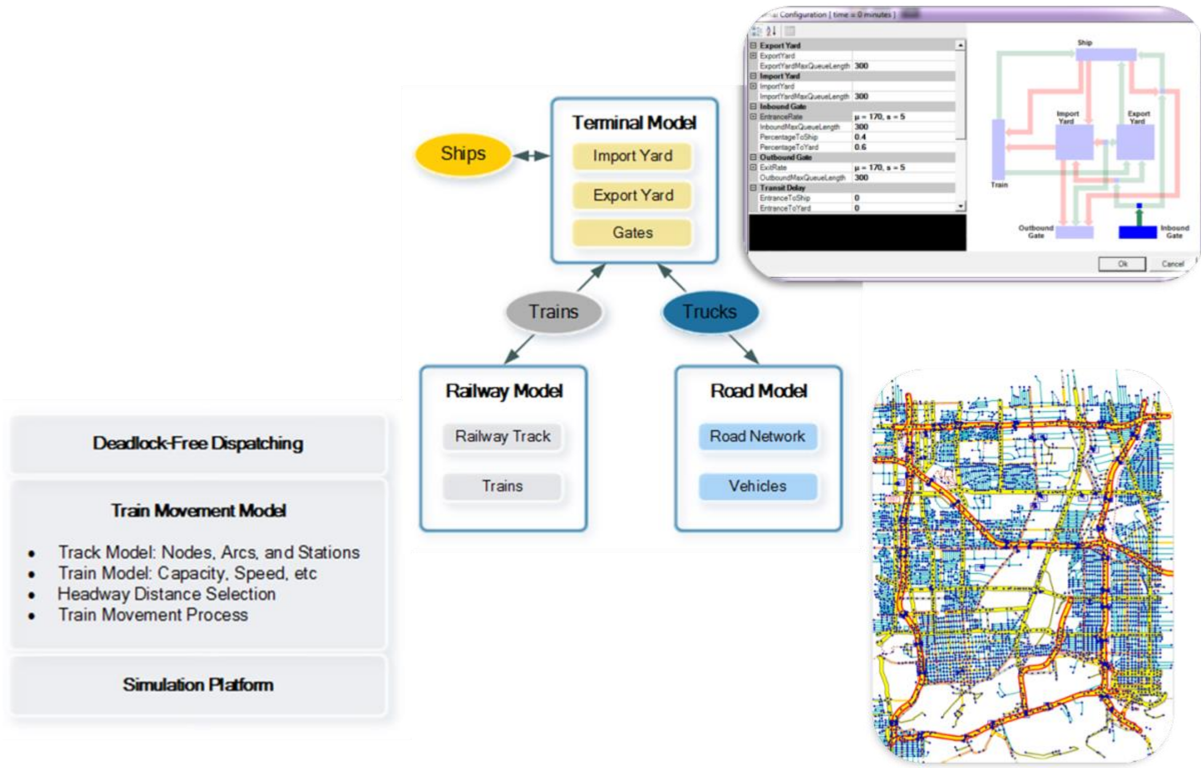

Figure 1. Simulation test bed

Below we described each part of the testbed shown in Figure 1.

Terminal Model

Figure 2 shows the main interfaces of the terminal model. One of the difficulties in combining the traffic within and in and out of a terminal model with the traffic in the road and rail network in real time as well as interactions with other modules such as the model/emissions model, terminal cost model is to describe these models in a programming language that makes it easy to interface each model in a continuous manner. For this reason, we developed an object-oriented, event-based terminal simulation module implemented with the C++ programming language based on our previous terminal model. It realizes high degree of continuous data exchange and software integration with the traffic simulation module via COM interface. The design of this terminal module is shown in Figure 1 that includes a terminal object and other three objects used to generate truck input & output, ships and trains. This terminal module provides a complete simulation environment where a lot of simulation parameters are able to be set such as inbound/outbound gate processing times, ship and train arrives, inflows and outflows of storage yards, yard capacities, etc. Various methods are supported for configuring the truck arrival: 1) setting the truck arrival distribution parameters in the user interface; 2) importing a truck log file that stores truck arrival quantities with respect to simulation time as simulation input; 3) obtaining truck arrivals from traffic simulation module via COM interface automatically. The terminal simulation module provides time dependent and cumulative graphs of any variable of interest within the terminal after running simulation successfully. With the developed terminal cost model, we can evaluate the impact on terminal operation costs of different scenarios. The use of C++ and object classes makes the model computationally efficient, expandable and reconfigurable.

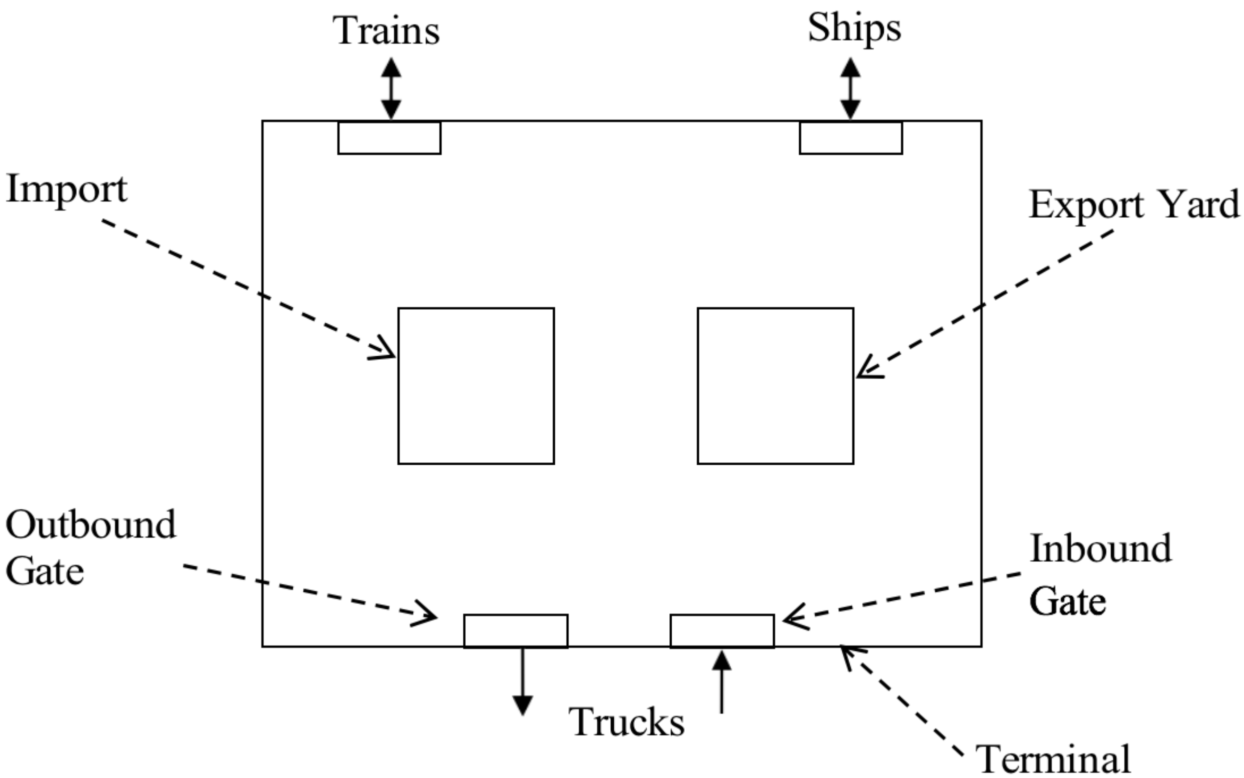

Figure 2. The terminal model

Microscopic Road Network Models

The microscopic traffic flow road network model simulates the vehicle movements on the roadway network. The model for a selected road network is built using the commercial software VISSIM. We first developed a microscopic simulation model of one selected area including more than 100 intersections (15 of them are signalized) as shown in Figure 3. Then based on the development of the selected area simulation model, we expanded the model to a large scale simulator in Fig. 3 having both freeways and local streets of the Los Angeles/Long Beach port area. We also finished the simulator coding of a larger scale simulator as in the simulator of Figure 4. In this microscopic model we implemented network coding including links, connectors, intersection controllers (stop signs and signal controllers), dynamic assignment etc. to evaluate the traffic flows in the area.

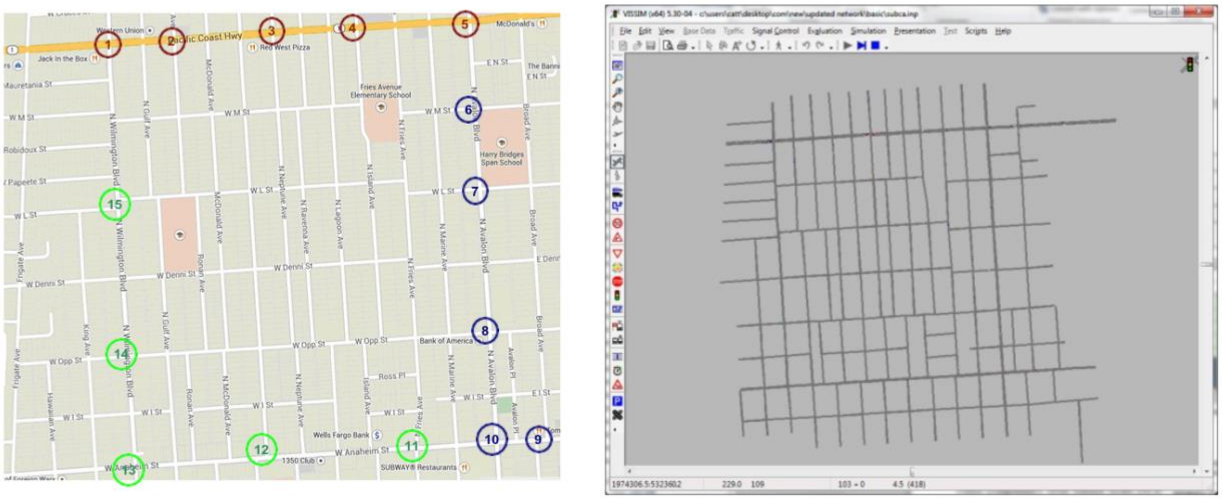

Figure 3. The microscopic road network model for a selected area

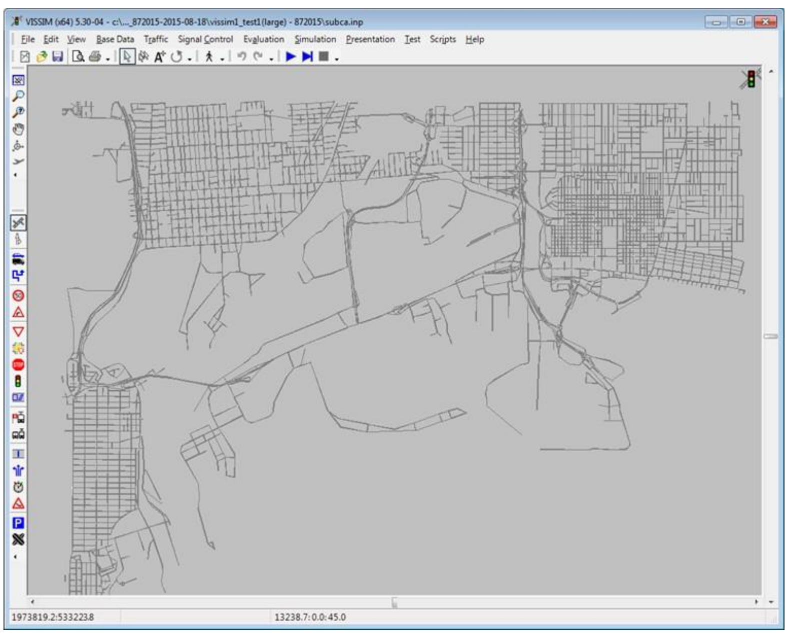

Figure 4. The microscopic road network model for LA/LB port area

The traffic simulator is set up to generate the following information:

- Data Collection Points are placed to measure the vehicle volumes, compositions and speeds of link flows every one minute;
- Queue Counters are used to monitor the queue length at intersections;
- Real-time vehicle information such as type, speed, acceleration, location, etc.;

- Detectors are used to simulate the vehicle detection function using inductive loops, track circuits or cameras;
- Network Performance Evaluation is used to get the network level performance measurements such as average delay, vehicle speed, and number of vehicle stops;
- Vehicle Record: We use the CMEM (Comprehensive Model Emission Model) vehicle emission model [9] to calculate fuel consumption and emissions using the outputted vehicle record file containing vehicle dynamics information that include vehicle IDs, speed and acceleration profiles after simulations are completed in order to compare the average vehicle emissions and fuel consumption of different scenarios.

External programs which execute COM commands have been developed to run the VISSIM model and provide access to model data which allows the integration of the road network models with other modules in the simulation testbed.

Macroscopic Road Network Models

The region covered by the macroscopic road network model of Los Angeles/Long Beach area is shown in Figure 5. We use the macroscopic traffic simulator VISUM to develop the macroscopic road network model to achieve fast network state predictions computationally. The simulator parameters including lane number, length, speed limit and road capacity etc. which are configured based on the actual transportation network. The inputs including passenger and freight traffic for the road network. They are expressed as the number of trips between zones that are the origins and destinations within the road network. We assume that the trucks can only carry one container so in our formulation the number of truck trips between each OD pair will be the number of containers to be delivered.

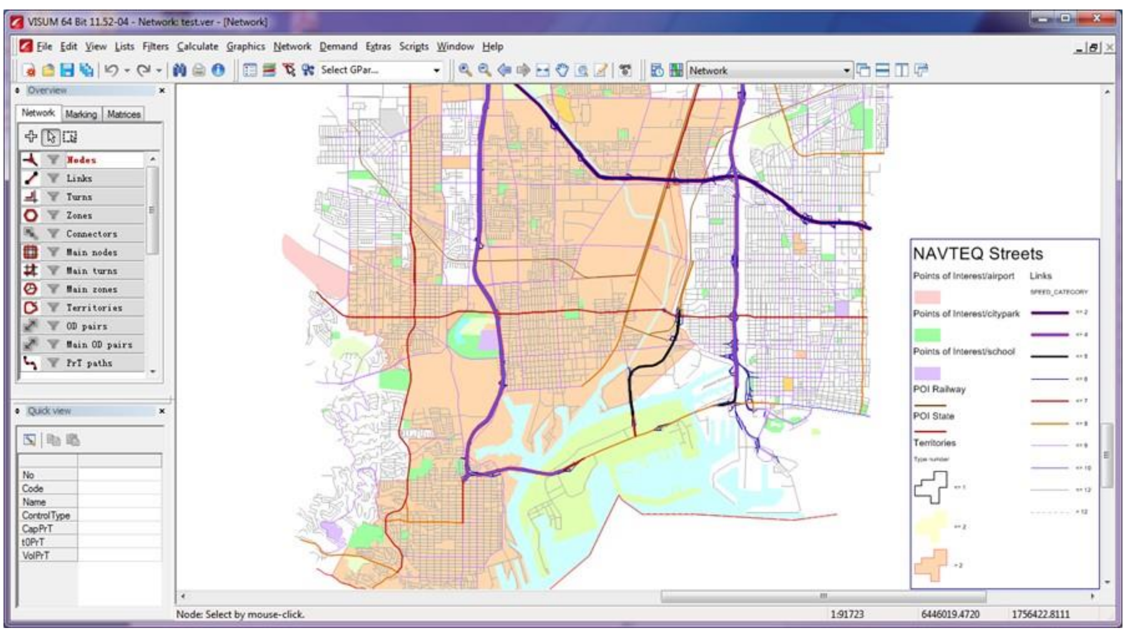

Figure 5. The macroscopic road network model for LA/LB port area

We expanded the above network to a larger scale area in Figure 6 in order to include warehouse areas and interactions with port activities.

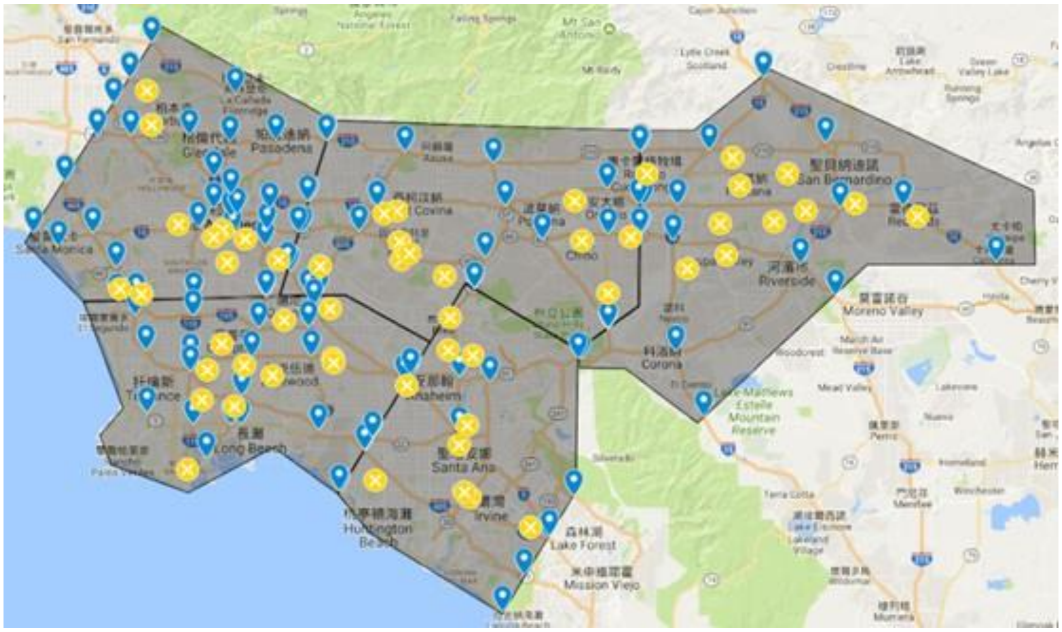

Figure 6. Larger macroscopic road networks

Considering the simulation time and optimization complexity, it is hard to support all the simulation and decision-making scenario in a large scale network. Scalability becomes a major issue in certain simulation scenarios where a centralized simulation model may not be able to generate fast solutions. Therefore, in this project we use a distributed simulation and optimization approach by decomposing the objective area into multiple sub-networks and modeling each sub- network with VISUM software, which provides good scalability and robustness of approach and supports efficient simulations of the traffic simulation of a much larger scale. The network decomposition considered the simulation load, optimization algorithm design, as well as freight flow distribution. The overall objective is to achieve balanced computational loads of different sub-networks. We evaluated the proposed decomposition approach using the south area of Los Angeles/Long Beach as shown in figure 7. We divided the area into three sub-networks and did comparison simulations of distributed and centralized simulations. The simulation results show that although the distributed approach has a 10%-20% deviation from the results generated by the more accurate centralized approach, it has a much better simulation efficiency compared to the centralized simulation model.

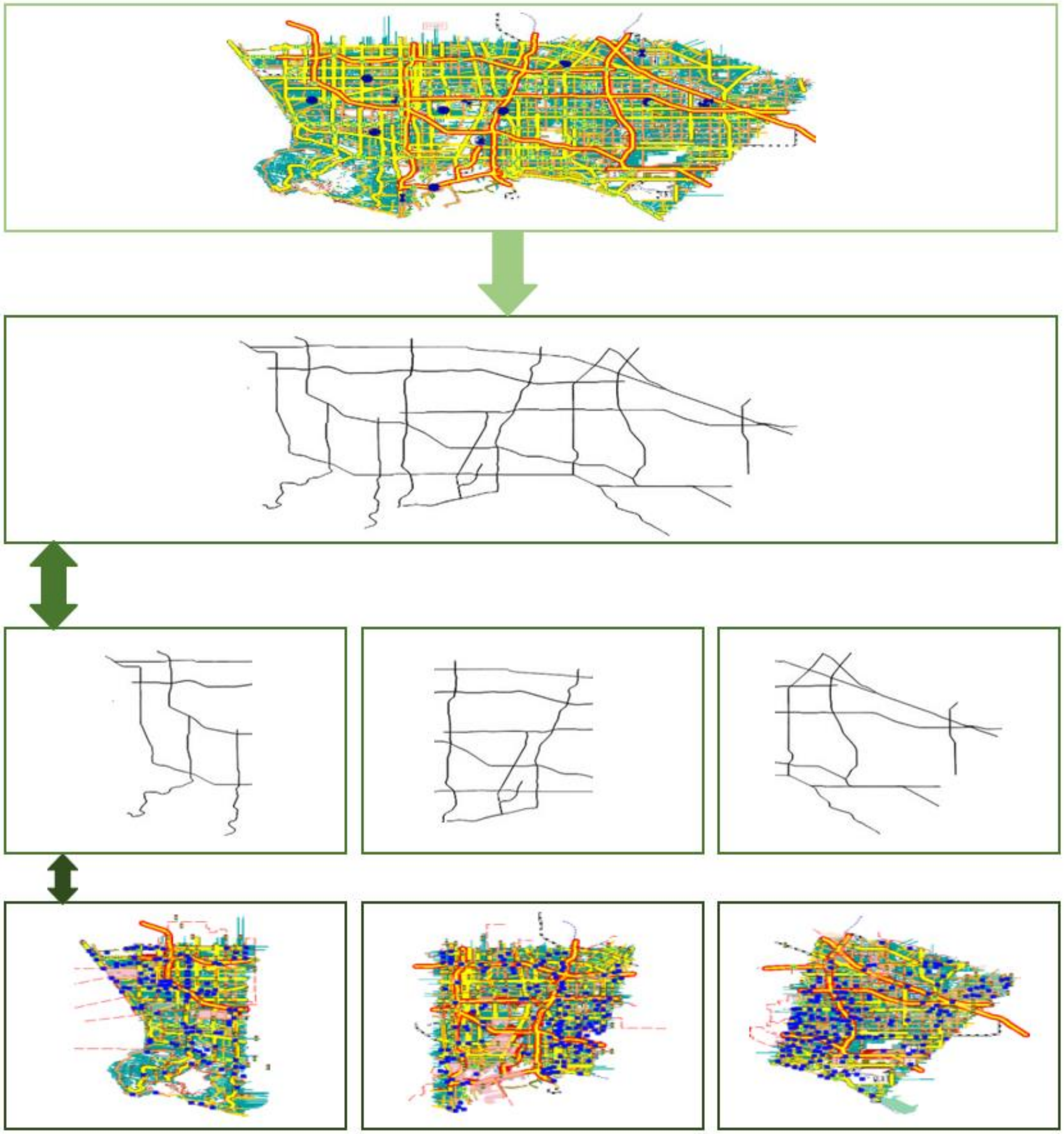

Figure 7. Example of network decomposition process

The distributed traffic models cover five sub-areas that include Long Beach, Los Angeles West, Los Angeles East, Irvine and San Bernardino. Those areas are connected via freeways in simulation. The impact of warehouse spatial dynamics has been tested in Long Beach area via a load balancing algorithm within a Co-Simulation Optimization control approach shown in the next section.

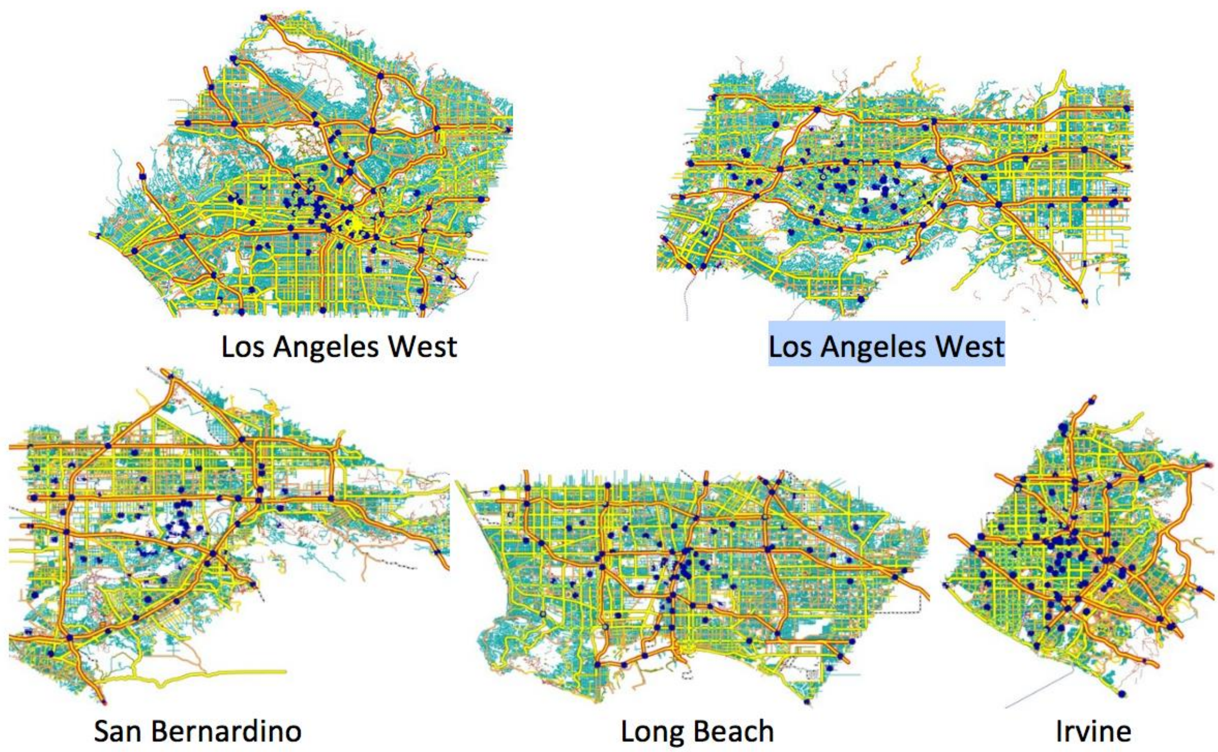

Figure 8. The macroscopic road network models for Los Angeles area

Historical passenger traffic data obtained from the Southern California Association of Governments (SCAG) are used to tune the macroscopic simulation models. The blue points in each sub-network are the warehousing locations after clustering of original locations of warehouses, which are also the origin and destination nodes in the simulation and algorithms. In this study we sue the Density-based spatial clustering of applications with noise (DBSCAN) as the warehousing clustering algorithm to group adjacent warehouses.

Co-Simulation Optimization Control Approach

Approach Overview

Based on the developments of microscopic and macroscopic simulation models, we proposed a Co-Simulation Optimization control approach in figure 9 as a framework for freight load balancing in a multimodal freight transportation network.

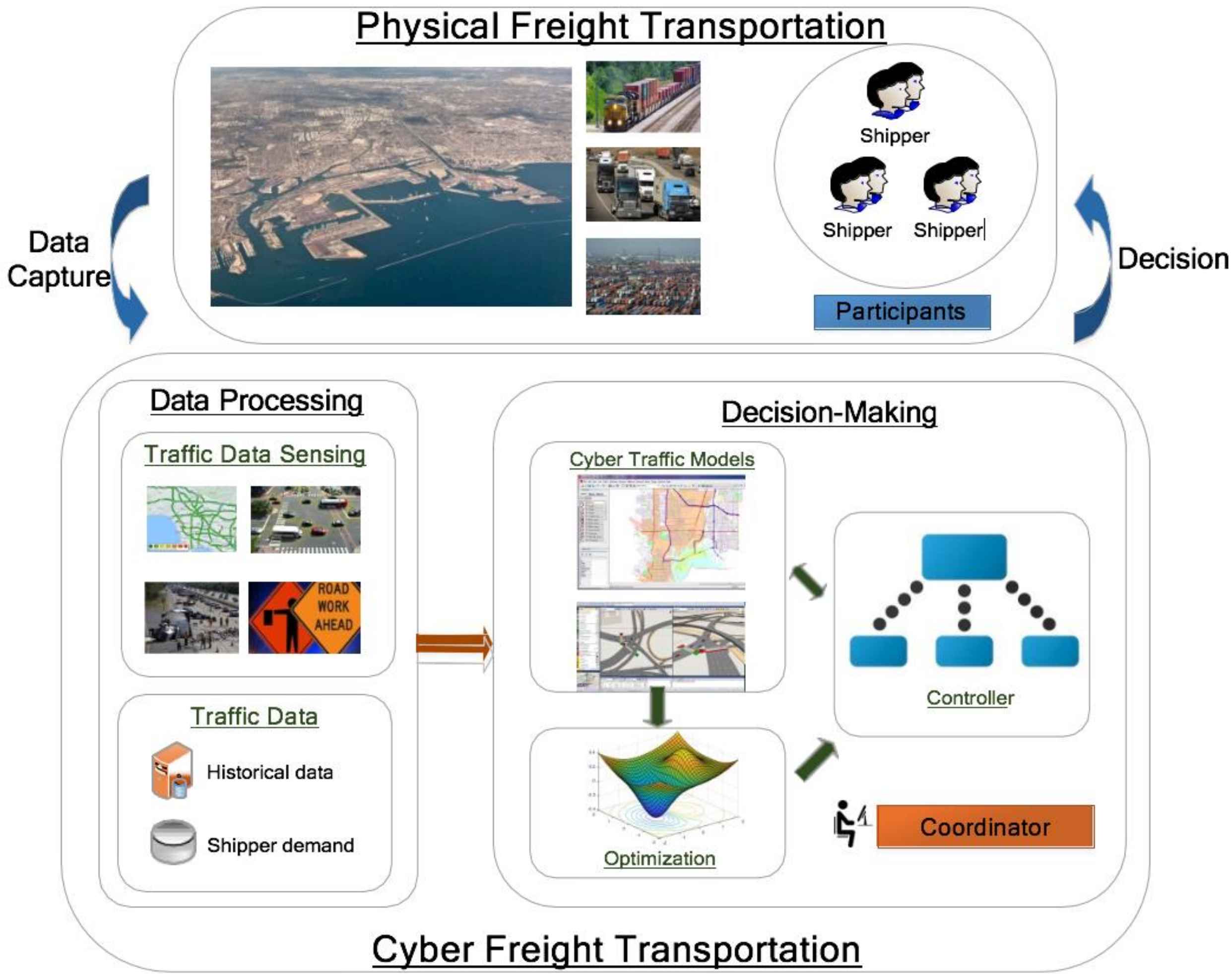

Figure 9. The Co-Simulation Optimization Control Approach

The proposed approach consists of the following modules:

- Traffic Data Sensing: This module connects the physical traffic network and the decision- making module. It involves the sensing of the physical transportation network data achieved by various available techniques including GPS (global positioning system), V2I (vehicle to infrastructure) & V2V (vehicle to vehicle) communication, sensor detection of the traffic status and incidents, etc. All the collected data are fed into the simulation model which reconfigures itself to match the measurements in order to provide accurate state and cost prediction for optimization.

- Cyber Traffic Models: The simulation models developed in this project are used to capture the main characteristics and dynamics of the multimodal transport network under the impact of the routing decisions, passenger traffic and network changes (network incidents, road closures, etc.) and land use dynamics. Simulation-based cost evaluation is used to estimate the intermodal state and cost which is required by the optimization algorithm of service decision-making.
- Optimization: An optimization algorithm searches for new candidate decisions that can reduce the total cost. Different optimization algorithms and configurations are applied based on the objective costs, network scale, and the availabilities of computation resource and solving time limitations.
- Controller: The controller manages the overall decision process until the predefined stopping criteria are met. The stopping criteria include reaching the maximum number of iterations or the change in the total cost is less than a predefined value between two consecutive iterations. Once one of the stopping criteria is satisfied the final decision is sent to the actual transportation network to implement the decision of freight traffic.

Centralized Load Balancing by Routing Freight

In this study we deal with the centralized routing of freight traffic that is container flow between origin and destination nodes. We assume all shippers send their demands to a central coordinator who generates individual routing decisions for each shipper by minimizing an overall delivery cost based on multimodal transportation network states. A multimodal freight transportation network can be represented as a directed graph consisting of a set of nodes (N) with a set of directed arcs (A) connecting the nodes. A node in the transportation network can be a road intersection, railway station, port terminal, or warehouse etc. An arc in the transportation network can be one segment of a roadway or railway track. Both passenger and freight traffic start and end at certain network nodes. Let I and J be the sets of origin nodes and destination nodes respectively. Both I and J are a subset of N.

In practice, the available freight vehicles are constrained in portions of the transportation network. For example, the number of available trains is limited between two rail stations or there is an upper bound for the number of assigned trucks among some truck depots. It is hard to describe and formulate these freight vehicle constraints with transportation nodes and arcs directly. Therefore, a multimodal service graph model is proposed to formulate the overall freight routing problem in this paper. The service graph G is also represented as a directed graph consisting of a set of service nodes (NS) with a set of modal segments (L) connecting these nodes. The set NS is a subset of N consisting of all origin and destination nodes as well as other nodes that support the formulation of freight vehicle constraints such as port terminals, truck depots, and rail stations. A modal segment is a transport segment served by a unique transport mode (e.g., road trucks or rail trains). An intermodal route from an origin node to destination node consists of a collection of one or multiple modal segments of the service graph that could be applied to deliver the demand between the corresponding origin and destination. The freight service graph can be seen as an abstracted upper layer of its corresponding physical transportation network. Figure 10 shows an example of a service graph and corresponding traffic network.

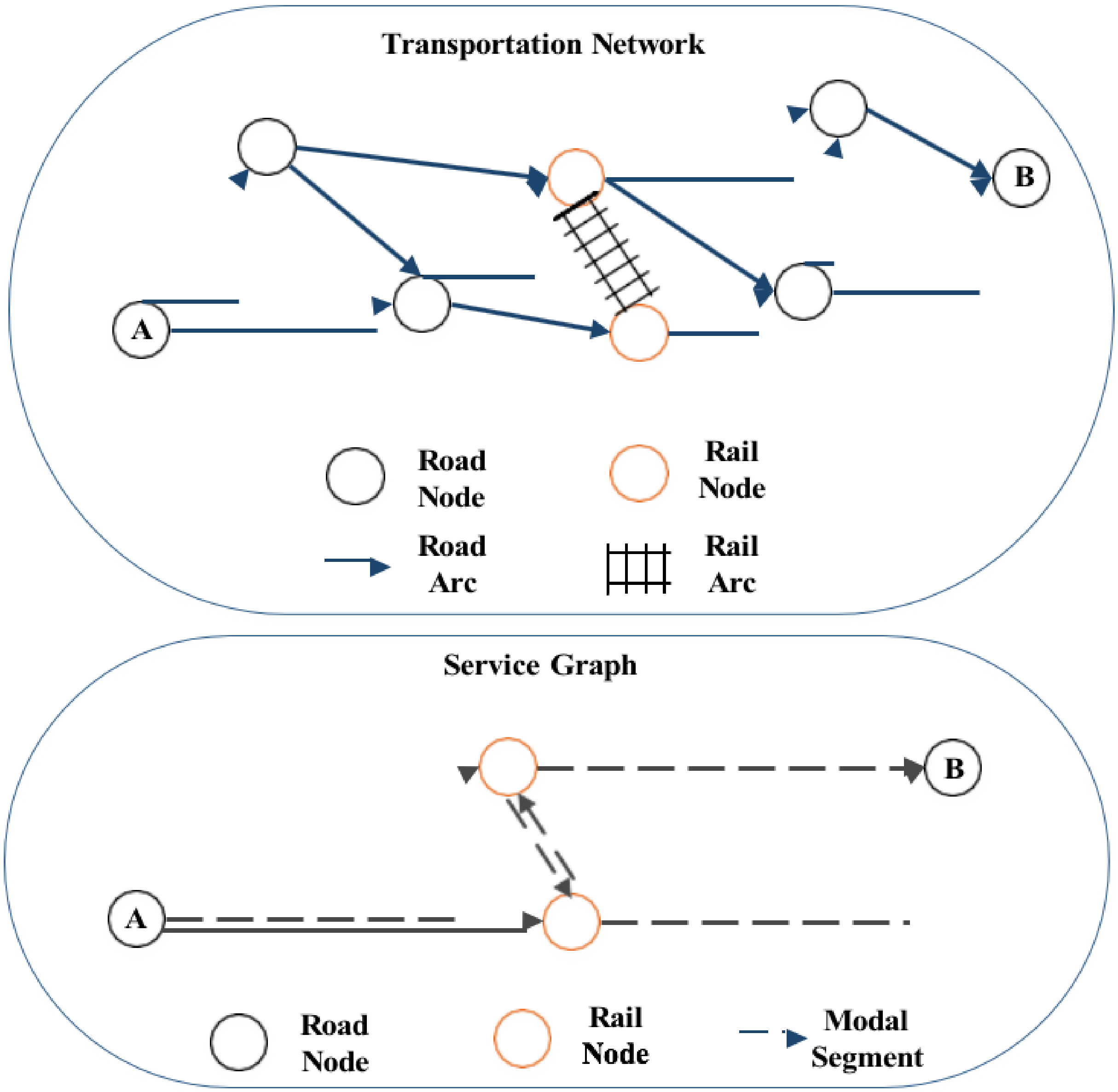

Figure 10. The traffic network and service graph

The overall freight routing problem in the central coordinator has two levels of decisions: the routing decisions i.e. freight load allocation in the service graph level and the freight vehicle dispatching in the transportation network. The routing decisions in the service graph that minimize the total cost depend on the transportation network dynamics (e.g., traffic congestion, arc travel time, vehicle setup costs etc.). Moreover, the transportation network dynamics are also impacted by the service graph decision since the travel time and congestion for a road segment or rail segment are determined by the allocated freight traffic. The constraints for allocating freight demand in a service graph include available modal segments and intermodal routes as well as the freight vehicle availability and capacity constraints while the freight vehicle dispatching constraints include transportation arc capacities and vehicle characteristics as well as other possible operation constraints such as safety headway between freight vehicles.

Application Examples

Traffic Signal Control with Truck Priority

We evaluated our proposed freight priority traffic signal control approach [10] with the developed microscopic simulation model in figure 3. The traffic flow in the road network is the average daily flow in Table 1 and the truck volume is 3%, 10%, and 20% of the overall flow respectively. The OD (Origin Destination) matrix is estimated from the daily flow by dividing the trip demands between ten different zones in the road network. The environmental impact variables shown in the tables such as fuel consumption, CO2 emission and NOx emission are computed using the vehicle emission model CMEM. We used two types of vehicles typical cars and trucks for the traffic demands. The distributions of their desired acceleration rates are show in Figure 11.

Table 1. Origin Destination Matrix

		Destination									
		1	2	3	4	5	6	7	8	9	10
	1	0	0	25	20	5	0	680	0	0	0
	2	0	0	3	3	3	3	3	3	0	0
	3	3	2	0	0	0	0	0	0	0	20
	4	2	0	0	0	0	0	0	10	5	5
Origin	5	5	5	0	0	0	0	0	20	0	0
	6	0	0	0	0	0	0	0	20	0	0
	7	670	0	0	0	0	0	0	30	10	10
	8	50	10	10	10	30	50	10	0	0	0
	9	0	0	0	5	45	5	0	0	0	0
	10	10	0	25	5	5	5	5	0	0	0

Unit: Number of Trips Per Hour

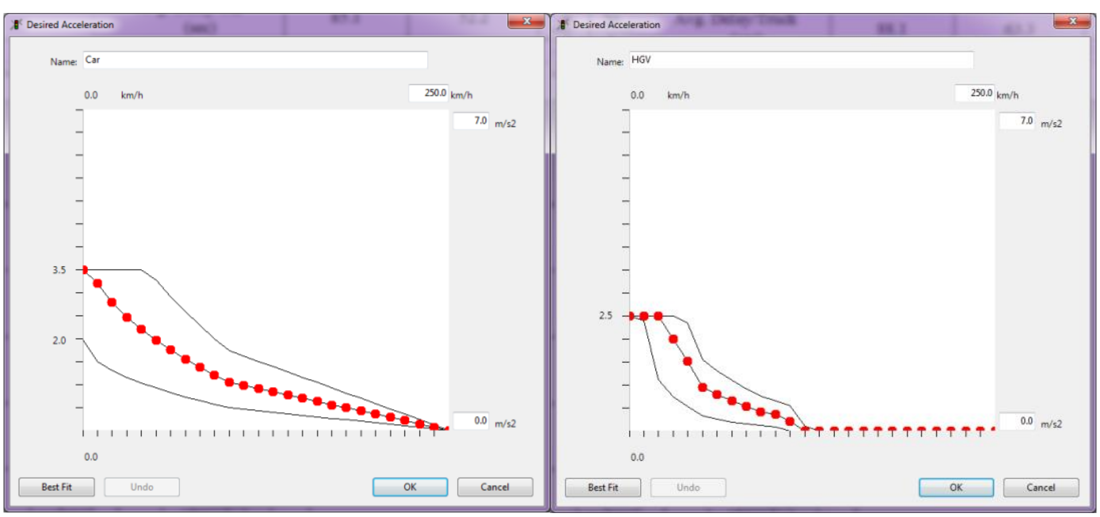

Figure 11. Desired acceleration rates of car model (left) and truck model (right)

The following benefits have been shown from the evaluation results: 1) The proposed traffic light controllers with truck priority using the proposed simulation models in the decision process improve the network performance by reducing the delay (about 28% to 45%) and vehicle stops (about 30%) as well as reducing fuel consumptions and emissions of CO_2 and NO_x compared to the fixed time controller which is the commonly used controller. The improvements are more significant when the truck volume is 20%. 2) Compared to controller without priority, controller with truck priority provides further improvements in the truck delay (about 5% to 10%) without affecting passenger vehicles whose travel time and number of stops have also been reduced. The fuel consumption and air pollution emissions of all vehicles involved have been reduced as a result of reducing vehicle delay and unnecessary stops. In summary, giving truck priority could benefit all vehicles involved and has a positive impact on environment.

Multimodal Freight Routing

With the developed macroscopic road network model in figure 5, we compared the proposed load balancing system in [11-12] with a system without a centralized coordinator for different changes in traffic conditions and demand. For the system without load balancing, we assume the shippers optimize their own daily routing decisions based on observing historical traffic conditions and thus they follow a user equilibrium based solution. However, we also assume that a shipper will not change its predefined decisions when other shipper demand or traffic condition are changed since this shipper does not have the information about demand changes to the other shippers without the coordinator.

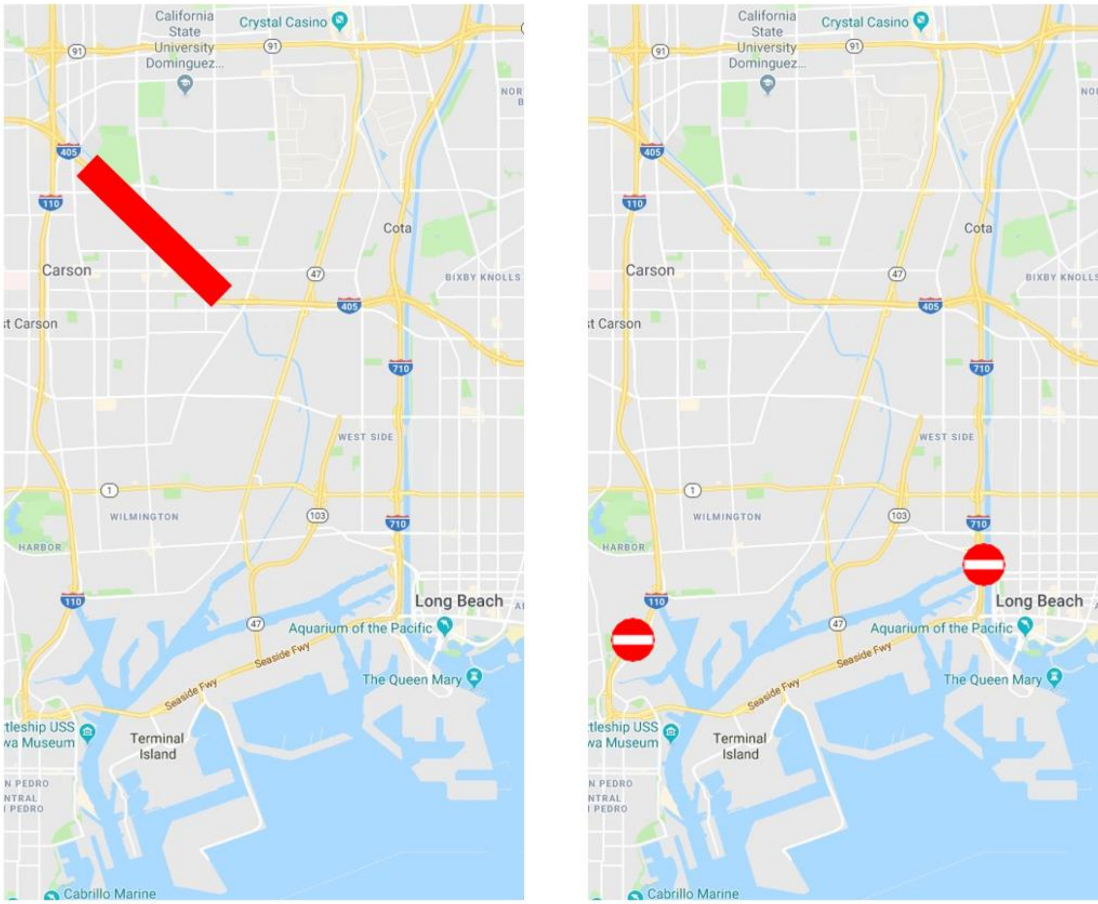

Figure 12. Traffic conditions a) I405 freeway congestion and b) freeway lane closures

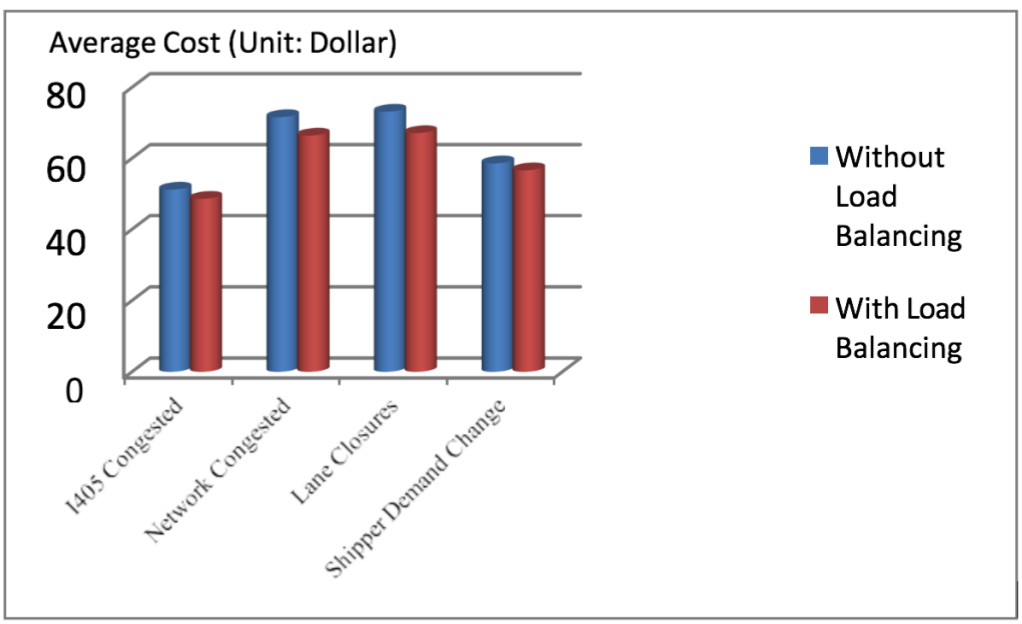

Figure 13. Load balancing impact for traffic condition and shipper demand changes

Figure 13 shows the impact of utilizing the proposed load balancing system in responding to traffic condition and shipper demand changes. In the first three cases, the traffic conditions are changed but the shippers' demand is the same as the baseline demand (see figure 12). In case 4 the demand of a shipper becomes two times of the baseline demand; however, there is no change on the road traffic condition. In all cases with load balancing, the coordinator can collect the shipper demand and traffic condition then make a centralized decision of redistributing the freight demand of the shippers across the multimodal network. According to the results, the delivery cost can be reduced in all the evaluated cases. The proposed load balancing system reduces the total cost by 6% to 9% compared to the cases without load balancing in the three traffic condition changes. For the last case, the average cost has been reduced by 2 dollars per container. Therefore, the simulation results show that the proposed system can generate better routing decisions for the participating shippers with a centralized coordinator.

Impact Analysis of Regional Land-use Dynamics

Over the last decade in Los Angeles, CA, warehouses and distribution centers have decentralized significantly from central urban areas to the outskirts. The extent of warehouse decentralization has been far greater than those of jobs and general population. Two primary factors for warehouse decentralization are increasing land values in the urban core and demand for logistics businesses to operate on a larger scale. The siting of warehousing and distribution facilities oriented to external trade would be locations with lower land prices and better access to freight transport infrastructure. Due to lack of actual shipment data, very few studies have empirically tested this relationship. A freight firm survey in Tokyo and a parcel survey in Paris documented that the truck VMT increased over time due to warehouse decentralization [5-7]. However, warehouses basically followed decentralizing shipment origins and destinations in these studies. In [8] the changes in warehousing and distribution of the Los Angeles area have been studied based on source data analysis.

With the developed macroscopic traffic flow road network in figure 8, we evaluated the impact of spatial distribution dynamics in Los Angeles area. Figure 14 describes the schematic of the imported freight flows which are transported through the Los Angeles/Long Beach ports, drayed to warehousing facilities and then delivered to local consumers as well as outside of California.

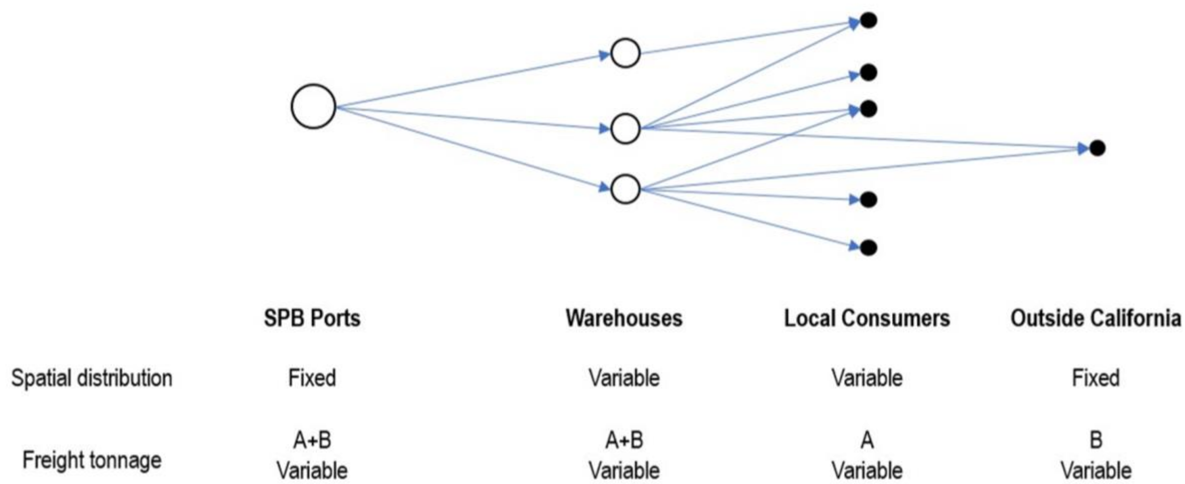

Figure 14. Import flows through ports in Southern California

In order to handle the large scaled and distributed simulation of the Southern California area, we proposed a multi-layer hierarchy Co-Simulation framework in figure 15. The procedure starts with an input to the service graph notifying the volume between each O/D pair. Then the O/D pairs are assigned to abstract graph based on load balancing algorithm. After that, the volume on arcs of the abstract graph is then interpreted as the O/D demand for abstract sub-graphs. For each abstract sub-graph, it then inputs O/D demand to the service sub-graph and let the service sub-graph do load balancing for each O/D pair. The volume on arcs of the service sub-graphs is then again interpreted as O/D demand for the corresponding traffic sub-networks. In the end, each traffic sub-network will perform load balancing for each O/D pair. If we denote the direction of control signal transition as forward, the direction of arcs cost updating can be seemed as backward.

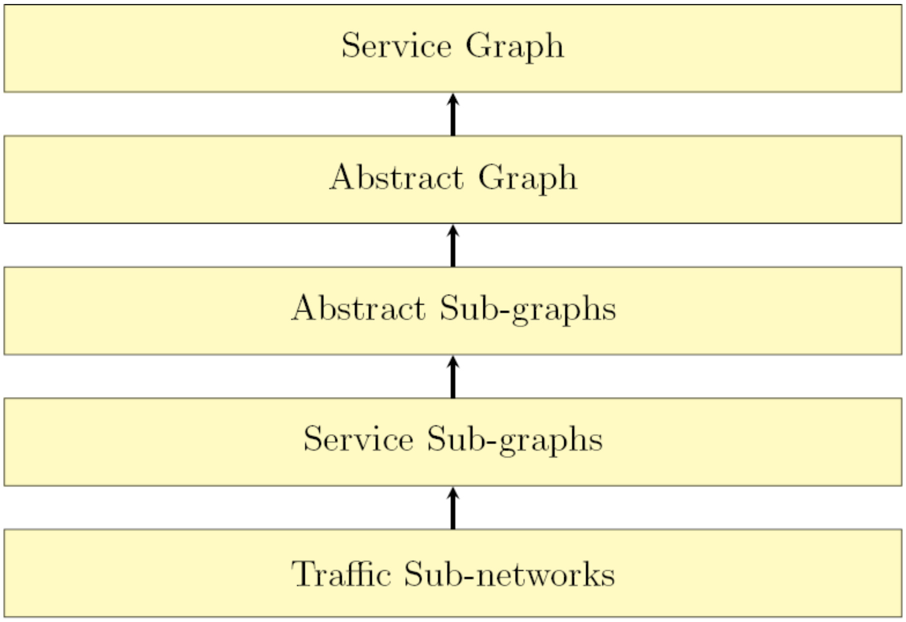

Figure 15. Multi-layer hierarchy co-simulation framework

For the warehousing distributions, we use the zip code based data from the County Business Patterns datasets of year 2003 and 2015 respectively. As for the customer demand data, we use the Longitudinal Employer-Household Dynamics datasets of year 2003 and 2015 respectively. In this study we set the total number of import containers of local consumers are 1755545 and 1667070 respectively. Due to lack of outbound data, we evaluated different outbound percentages. The outbound percentage is defined as:

$$\textit{outbound percentage} = \frac{\textit{outbound demand}}{\textit{inbound demand}} \times 100\%$$

Table 2. Evaluation Results

Outbound Percentage	2003 CustomerDemand				2015 CustomerDemand			
	2003 Warehousing		2015 Warehousing		2003 Warehousing		2015 Warehousing	
	Total*	Average+	Total*	Average+	Total*	Average+	Total*	Average+
0%	8.106	4.617	8.446	4.810	7.444	4.465	7.861	4.716
20%	12.097	5.742	12.522	5.944	11.081	5.539	11.853	5.924
40%	17.259	7.022	18.229	7.416	16.175	6.931	17.351	7.434
60%	22.092	7.865	23.279	8.288	20.783	7.791	22.048	8.266
80%	27.311	8.643	28.363	8.976	25.650	8.548	26.872	8.955
100%	32.260	9.189	33.237	9.466	30.391	9.115	31.691	9.505

* - total cost unit: million hours; + - average cost unit: hours per container

Table 2 summarizes the evaluation results of different scenarios. From the simulation results, we can draw the following conclusions:

1. By increasing the outbound percentage, the average costs will increase in all evaluated scenarios due to the added deliveries with longer distances;
2. With decentralized warehousing of year 2015, both the total and average costs have increased compared to 2003 warehousing distribution.
3. With the warehousing in 2003 the costs have increased slightly more than the cases with warehousing in 2015 in most cases, which indicates that the decentralized warehousing has some advantages to deal with increasing outbound freight flows.

Conclusion

In this study we developed regional simulation models that allow us to investigate the impact of various technologies and policy changes on the Los Angeles/Long Beach port and surrounding areas. The work of developing regional simulation models in this project consist of an improved terminal simulation model, microscopic and macroscopic road network simulation models, as well as associated programs/algorithms accessing those models. The developed simulation models are used to evaluate and analyze different proposed systems including freight priority traffic signal control, regional multimodal freight routing, and analysis of local warehousing dynamics in Los Angeles area.

The examples of using the developed simulation models demonstrate the promising applications of simulation techniques. The fast-forward simulation models could provide far more accurate information of system dynamics compared to simple mathematical model based approaches. The developed traffic simulation models could be used in real time for optimization, control and routing as well as for evaluations before actual implementation.

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