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Evaluating Twin Cities Transitways' Performance and Their Interaction with Traffic on Neighboring Major Roads

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16. Abstract (Limit: 250 words)

Long-term, regional travel demand models are essential tools used by planning organizations for resource management, project scheduling, and impact studies. Developed primarily at the macroscopic level, these tools lack sufficient detail to capture the influence of local geometry, dynamic traffic controls, or advanced transportation demand management (ATDM) strategies. To bridge the gap, a hybrid mesoscopic-microscopic model was developed. The core of the model, surrounding two light rail corridors in Minneapolis-Saint Paul, Minnesota, was developed at high resolution for microscopic simulation to capture the interaction between traffic signals, transit systems, and the road network. The remainder of the greater Twin Cities area was implemented based on the Regional Planning Model (RPM) maintained by the Metropolitan Council. Interfacing the Aimsun-based hybrid model with the Cube-based RPM, the Twin Cities Metro Hybrid Simulation was used to iteratively improve mode choice and traffic assignment to achieve a dynamic user equilibrium state. Important lessons were learned regarding the effort required to develop and maintain such a model with implications for future large scale regional modelling.

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Evaluating Twin Cities Transitways' Performance and their Interaction with Traffic on Neighboring Major Roads

Final Report

Prepared by:

John Hourdos
Derek Lehrke
Minnesota Traffic Observatory
Department of Civil, Environmental, and Geo- Engineering
University of Minnesota

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Executive Summary

Long-term, regional travel demand models are essential tools used by planning organizations for resource management, project scheduling, and impact studies. In most cases, these tools are developed at a macroscopic level, including only the most basic information about the road networks' geometry and traffic parameters. The development of the Green Line light rail corridor between the two Twin Cities downtown areas represented a modeling challenge for the Twin Cities Regional Planning Model (RPM) due to complicated road geometries and traffic controls. To explore this issue and a potentially better alternative analysis methodology as well as perform a before-after study, a different modeling approach based on traffic simulation and Dynamic Traffic Assignment (DTA) was developed and is presented in this report. Toward that end, a large-scale simulation was constructed to capture localized, high-resolution data and incorporate accurate transit and signal information while maintaining a wide, regional scope sufficient to capture long-distance travel and dynamic rerouting.

Large-scale traffic simulation is by itself a very new capability allowed by recent advancements in traffic modeling as well as computer hardware and software. To that extent, very few examples of large-scale simulation are available and there are even fewer attempts to integrate DTA traffic simulation with a travel demand model. Even more, in this project a new approach for traffic simulation is utilized by using a simultaneous operation of two modeling resolutions, a microscopic level model for the core network around the two LRT Transitways and a mesoscopic level model for the rest of the metropolitan area. This Hybrid traffic simulation scheme provides for great detail in the project area without compromising route selection for trips originating and destined outside of it. The challenges were many for the implementation of this very new methodology and tool. Some of the challenges involved the development of the network geometry while maintaining a link to the RPM, the calibration of this large model, the designing of efficient experiments that minimize overall project duration and effort, and novel ways of visualizing the produced results since traditional approaches are not applicable to such a large network.

This report describes the complete development of the hybrid model. As a primer, descriptions of similar projects are given along with broad background on varieties of simulation, culminating with the Aimsun hybrid simulation. The implementation of the geometric, traffic control, and vehicle demand components of the hybrid network is then described, including details regarding the two alternative models: one for the existing Green Line along University Ave., and one for the no-build alternative. Alongside the construction of the Aimsun model, interconnections to the Regional Planning Model in Cube Voyager were maintained.

Throughout the development of the Aimsun hybrid model, calibration and validation efforts were undertaken to ensure the hybrid model would both align with the RPM and also produce representative results according to real network data. Calibration within this framework refers to adjustments made to network or vehicle parameters, which aimed to correct irregularities within simulated behavior. Calibration/Validation took place in steps, starting with the macroscopic level where an agreement with the RPM was established. This step was necessary since the hybrid and RPM models are designed over different software platforms each with its own abstractions and network coding ways. Four main

issues were identified and corrected as part of the macroscopic calibration process: self-centroid trips, unusual centroid configurations, volume-delay functions, and High Occupancy Vehicle behavior. The second step involved the calibration of the core microscopic parts of the model. This step ensured that reasonable traffic patterns were formed in the simulated arterials and freeways and ensured the correct operation of the 700+ traffic signals including LRT preemption and priority rules. Once the subarea networks were integrated into the larger regional hybrid model, manual calibration techniques became unusable due to the immense breadth of the network and the significant time cost to perform each iteration of simulation. As such, alternative calibration strategies were developed. These 'blanket calibration' techniques involved adjusting parameters for larger blocks of the network simultaneously, either by region or by targeting a particular subset of the network (e.g., all roads of a certain type, all nodes, etc.). The validation of the hybrid model was based on intersection turning counts provided by the cities of Minneapolis and St. Paul in various formats and from varying time periods and loop detector counts on freeway sections provided by MnDOT. During this process the research team had to also deal with numerous bugs still present in the software.

Both project objectives were accomplished although the original plan and methodology had to be modified to accommodate the aforementioned challenges. The integration with the RPM Mode Choice step was accomplished and showed that it is feasible to upgrade the traditional static traffic assignment step with a Dynamic User Equilibrium based hybrid traffic simulation one. Although further improvements relating to the overall process are still needed, this proof-of-concept ensures that an integration with the new activity-based RPM is possible and potentially even more efficient and accurate.

The comparison of the Green Line corridor with and without the LRT has produced credible results confirming that although the reduction in capacity of University Ave, does affect neighboring streets, the larger effect is absorbed by I-94 with only a marginal increase in travel times and reductions in speed. It is important to note that the model indicated the existence of instabilities on major intersections of the corridor where the selected traffic control plans play a big role in the system's efficiency. Indicative results are presented both for the morning peak period (6:45 -7:30 AM) as well as the afternoon peak (3:00 to 4:00 PM), while a full result set for both peak periods is also available.

The report concludes with a collection of lessons learned involving the development, calibration, and management of a large simulation model highlighting the challenges and suggesting an optimal course of action for future projects.

1. Introduction

Long-term, regional travel demand models are essential tools used by planning organizations for resource management, project scheduling, and impact studies. In most cases these tools are developed at a macroscopic level, including only the most basic information about the road networks' geometry and traffic patterns. In Minneapolis-Saint Paul, Minnesota such a model was developed and is maintained by the Metropolitan Council. The development of the Green Line light rail corridor between the two downtown areas represented a modeling challenge due to complicated road geometries and traffic controls. The Regional Planning Model (RPM) may not be sufficient for analyzing the impact and operations of a new transit line on one of the most central links of the network. To explore this issue and perform a before-after study, a different modeling approach based on traffic simulation and Dynamic Traffic Assignment (DTA) was developed and is presented in this report.

Macroscopic regional models such as the RPM lack several key elements needed for close examination of infrastructure and systems such as the Green Line light rail. Localized geometric effects are not captured by low-resolution models, causing errors in speed estimation, delay, etc. Traffic controls are often absent or simplified; impacts from actuated signals, coordinated signal corridors, or preemption/priority strategies are lost. Static traffic assignment models also fail to capture the dynamic nature of traffic, such as allowing vehicles on congested routes to reroute. Thus, a gap exists between current regional macroscopic models and their ability to model fine details and active traffic management (ATM) or advanced transportation demand management (ATDM) systems.

To address this gap, a large-scale simulation was constructed to capture localized, high-resolution data and incorporate accurate transit and signal information while maintaining a wide, regional scope sufficient to capture long distance travel and dynamic rerouting. Simulation models incorporating large regions allow more realistic route selection, especially for vehicles traversing congested areas. By focusing on a small sub-network consisting of only the corridor of interest, vehicles are trapped onto only a few paths which may become severely congested. Expanding the model to include surrounding parallel routes frees vehicles to bypass congestion appropriately.

Similarly, a significant extent of the transit network is required to adequately capture movements through and around major corridors. In this case, trips which include the Green Line light rail transit (LRT) corridor are surrounded by other modes; riders must reach the light rail and, ultimately, their destination by other methods. Numerous bus lines act as collectors for the Green Line, feeding riders into the railway from outlying urban and suburban areas. To capture such multimodal trips, wide swaths of the metropolitan area must be included in modeling efforts.

The resolution of the model is a significant problem for such a simulation effort. High-resolution modeling is necessary throughout the corridor of interest; only microscopic models incorporate traffic control with sufficient detail to accurately describe the interaction between light rail vehicles and the road network. However, simulating large regions at a microscopic level quickly becomes computationally prohibitive and difficult to construct and maintain. To counter this, mesoscopic simulation techniques have been developed which sacrifice some detail but are capable of simulating larger areas efficiently. Part of this sacrifice includes traffic control which is vital to modeling the light rail corridor.

The approach in this project was to develop a hybrid model, incorporating components of both microscopic and mesoscopic modeling to achieve both the high resolution required along the light rail corridor and the wide scope necessary for accurate route and mode choice. A core region, including the Green and Blue Line light rail corridors and both Minneapolis and Saint Paul downtown districts, was implemented at a microscopic resolution, with the remainder of the metropolitan region modeled at a mesoscopic level. By operating both levels in conjunction, sufficient detail and control were maintained in the corridor of interest while still retaining a wide scope to capture alternative routes for vehicles avoiding congested areas.

The hybrid model was linked to the original RPM to allow for mode shift between iterations, completing the feedback loop for the model. Speed data for every link in the network were returned to the RPM to inform a new travel demand and mode choice. By introducing this connection, traffic behavior within the Green Line corridor can make an impact on travel decisions and transit use throughout the network and more appropriately reflect reality.

This report describes the complete development of the hybrid model. As a primer, descriptions of similar projects are given along with broad background on varieties of simulation, culminating with Aimsun hybrid simulation. The implementation of the geometric, traffic control, and vehicle demand components of the hybrid network is then described, including details regarding the two alternative models: one for the existing Green Line along University Avenue, and one for the no-build alternative. Alongside the construction of the Aimsun model, interconnections to the Regional Planning Model in Cube Voyager are outlined.

As the model was developed, calibration and validation efforts were also undertaken to ensure proper fitting of the Aimsun hybrid model to both the Regional Planning Model and real data (in the form of loop detector and turning count data). These efforts were made at multiple stages, including at all resolutions from macroscopic to microscopic. Within the integrated hybrid model, calibration and validation became significantly more difficult due to the size and scope of the task, as well as multiple issues related to Aimsun's specific implementation of hybrid modeling. Methods for overcoming these barriers conclude the discussion of calibration.

With the hybrid model completed and calibrated, the results are presented in Chapter 5. They relate to both the integration with Voyager and refinement of mode choice within the RPM, as well as the impact of the Green Line on University Avenue and the microscopic subareas of the hybrid model.

The final chapter of this report includes significant details and commentary regarding the successes and difficulties of this project. Many important lessons were gleaned through overcoming barriers to achieving such an ambitious simulation scope. These include methodologies related to implementing and calibrating such models, alongside information related to handling and effectively visualizing such large and complex data sets.

2. Background

A few other attempts have been made at large-scale and hybrid simulation for major metropolitan regions across the world. A macroscopic-microscopic iterative solution was developed for the Des Moines, Iowa region relying on a small microscopic model for peak-time speed estimation to improve macroscopic demand modeling (1). The mesoscopic model DynusT has been employed by several teams working to improve regional planning models, notably for Seattle, Washington (2) and Sacramento, California (3). In each case, the formerly macroscopic tools used by the cities were interfaced with a mesoscopic model to provide additional modeling accuracy.

Similar to the approach describe within this paper, Burghout and Wahlstedt (4) targeted a small portion of Stockholm, Sweden and examined the redistribution effects from new signal control plans within a dense, bus-priority arterial corridor by integrating VISSIM's microscopic modeling capabilities with MEZZO, an event-based mesoscopic model. VISSIM was also paired with Synchro and San Francisco, California's regional travel demand model CHAMP (5) to develop a long-term planning framework for analyzing bus rapid transit (BRT) and multimodal transportation scenarios.

Finally, the New York City Department of Transportation developed a large-scale mesoscopic-microscopic simulation model of Manhattan and surrounding arterials. Using the framework of the existing regional travel demand model, successive layers of mesoscopic and microscopic models were implemented on the Aimsun platform (6).

2.1 Modeling Strategies

Four modeling approaches are encountered throughout the methodology presented in this report: macroscopic, mesoscopic, microscopic, and hybrid. Some basic knowledge of each is necessary for understanding the challenges encountered while constructing the Twin Cities Metro Hybrid Simulation Model.

2.1.1 MACROSCOPIC MODELING

Covering the broadest scope at the lowest resolution is macroscopic simulation. The Regional Planning Model which forms the base of this process is a macroscopic tool, including only major roadways and intersections (referred to as links and nodes, respectively) in a "stick network". Social and economic data are utilized with demand generation and mode choice models to create trip origin/destination tables which are used for static traffic assignment (STA). The parameters of importance are link speed, capacity, and assigned traffic volume; vehicles are not individually modeled but are instead aggregated into link demand.

2.1.2 MICROSCOPIC MODELING

Microscopic models are high-resolution with great detail in terms of geometry and control. Car following, lane changing, and other driving behavior models are used within a fixed-time-step framework as vehicles propagate through the network making decisions which cumulatively produce traffic patterns. Vehicle behavior is governed by parameters such as reaction time, acceleration and deceleration rates, gap acceptance, and so forth. Accurate geometry and signal timing affects queuing at intersections and congestion buildup throughout the network. Each traffic signal, intersection turning movement, and roadway link must be calibrated to mirror behavior in the real world.

2.1.3 MESOSCOPIC MODELING

Although the term "mesoscopic" covers a range of techniques, it will be used here in relation to the mesoscopic simulation methodologies within the Aimsun platform. Aimsun's mesoscopic model uses a slightly improved stick network which includes each lane rather than simple links, along with a discrete-event based system to track events within the simulation. The Aimsun manual lists six types of events which are treated:

- Vehicle generation (Vehicle Entrance)
- Vehicle system entrance (Virtual Queue)
- Vehicle node movement (Vehicle Dynamics)
- Change in traffic light (Control)
- Statistics (Outputs)
- Matrix changed (Traffic Demand)

These events happen as necessary and are placed into a time and priority list for processing. As such, the mesoscopic simulator does not rely on a single 'simulation step' time increment.

As individual vehicles enter the network from centroids, they are placed into virtual queues waiting to enter sections. The simulator determines headway times for entering vehicles and assigns arrival times for each to signify the moment the vehicle will appear at the entrance to the section. As the vehicle traverses their path, they will interact with various sections and nodes, each of which will estimate the travel time for the vehicle to the next event location (section to node, or node to section).

In both of these cases, the capacity of the section or node (OR roadway or intersection) is determined based on three parameters: jam density, length, and number of lanes. The capacity is in turn used to drive car-following and lane-changing models to determine the fastest time, based on current conditions, for the vehicle to traverse the section or node turning.

Within the nodes, vehicles queue to enter the intersection and traverse to their exit section. A priority system selects the order to allow vehicles through and, once selected, updates the departure times for all subsequent vehicles in queue which are affected (i.e., those that use the same turning or section). In this way, if a vehicle is delayed in moving through the intersection by conditions downstream, the subsequent line of vehicles are also delayed appropriately, pushing the congestion upstream.

2.1.4 HYBRID MODELING

The model developed for this task is a hybrid model incorporating a core microscopic simulation region surrounded by a much larger mesoscopic region. In order to understand the issues regarding developing the simulation and the results derived therefrom, this section will use the previously described mesoscopic and microscopic simulation methodologies used within Aimsun and how they are incorporated into hybrid simulation. With the integration between microscopic and mesoscopic modeling in hand, the final piece of understanding for the Aimsun simulation is the type of traffic assignment being performed. In the case of this project, the hybrid model used primarily a heuristic approach to reach a Dynamic User Equilibrium (DUE).

Hybrid Integration

While microscopic simulations provide the highest resolution of data, they are memory and computationally intensive. Mesoscopic simulations require less resources to complete, but do not offer the same level of detail. Using a high-resolution, microscopic simulation core surrounded by a lower-resolution, mesoscopic outer layer, regions of particular interest can be examined fully while reducing the total computation expense. Additionally, including a mesoscopic allows for vehicles to find routes outside of the microscopic region if congestion or incidents cause significant disruptions in the microscopic areas (see Figure 1, (7, pg442)).

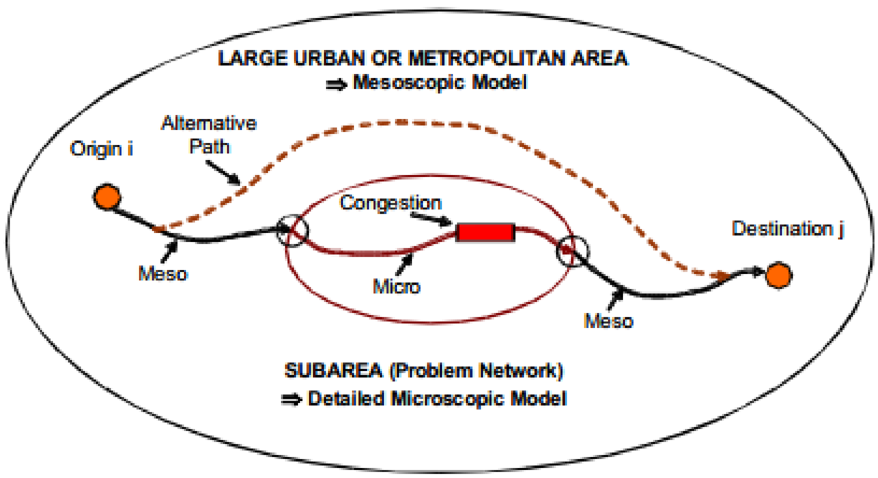


Figure 1. Hybrid modeling to locate alternative paths.

Within the focus area (microscopic simulation), the primary path between the origin and destination develops congestion. If only the microscopic region is considered, no alternative is available and vehicles must wait through the congestion with large delays. However, if the mesoscopic region is also included, vehicles moving from origin "i" to destination "j" can select alternate routes which do not utilize the affected links. In this way, a more accurate representation of driver decision making can be modeled and the high level of detail is maintained within the corridor of interest, but computing needs are dramatically reduced (compared to simulating the entire region microscopically).

While the mesoscopic regions are, as noted above, modeled using an event based approach, the microscopic region uses a fixed time interval to 'step' through the entire simulation period. To merge these two disparate approaches, a single simulation clock is used to synchronize events between the two portions of the model. All vehicles also maintain state parameters relevant for both the microscopic and mesoscopic regions, allowing vehicles to freely move back and forth between the two and use the appropriate car-following, lane-changing, and path selection models.

Dynamic User Equilibrium

To distribute vehicles across the network, Aimsun performs a dynamic traffic assignment based on a formulation by Ran and Boyce (8):

> *If, for each OD pair at each instant of time, the actual travel times experienced by travelers departing at the same time are equal and minimal, the dynamic traffic flow over the network is in a travel-time-based dynamic user equilibrium (DUE) state.*

As vehicles are loaded into the network, they select shortest paths based on travel time. With large networks, the potential number of paths for every O/D pair become too numerous to model effectively. To counter this, Aimsun limits the number of paths available to each O/D pair and allows this limit to be specified by the user. For this report, the number of paths per O/D was limited to ten. Once the set of paths have been determined, the remaining volume is loaded onto those paths using a Method of Successive Averages (MSA).

This procedure is repeated N times, terminating once some upper limit on iterations has been reached (in this case N = 25), or once the simulations are sufficiently similar. This second criterion is based on a statistic called the Relative Gap or R-Gap. The R-Gap, proposed by Janson (9), is the ratio of 'excess delay' experienced by all users as compared to their possible minimum paths. Simulations terminate once the R-Gap is below 2%. These parameters were chosen due to the computational limitations of the model. This issue is explained in detail in the "Lessons Learned" section of the report.

Dynamic Traffic Assignment

While the method of loading the network that was ultimately chosen for this project was the Dynamic User Equilibrium described in the previous section. Another method was used during the calibration portion of the project was the Dynamic Traffic Assignment. However it should be noted that DTA is a general term encompassing a variety of problem definitions, formulations, and algorithmic solution procedures. The DTA in general is more advanced form of traffic modeling then the current standard of static traffic assignment that uses a series of volume-delay functions (VDF) to express the delay experienced on each successive link. These VDF's cannot take into account things such as weaving, traffic signals, lane merges, or single lane breakdown on multilane roads. It also does not take into account time into its route choice step. In other words it cannot account for the fact that if a vehicles leaving the same Origin and going to the same Destination may have different paths depending on when they depart. While the differences in DTA and static traffic assignment are extensive this section is primarily focused on how DTA is defined and used in Aimsun.

The major difference in the DTA simulation vs the DUE simulation is that while the DUE iterates until some level of convergence defined by the R-Gap or maximum iterations allowed. The Dynamic Traffic Assignment Stochastic simulation does only one iteration of the model. Since only one iteration of the model is completed vehicles need to have a way defined on how they are going to choose their path. Aimsun allows the user to select which algorithm of route choice would be use including Binomial, C-logit, logit, Proportional, Fixed Based on Free flow, or to define their own. Both the DUE and DTA have a "Cycle" length that must be defined that determines how many slices the simulation period will be split into. At each one of these slices new shortest paths are calculated. The DTA model however also allows a user defined percentage of vehicles to reroute at each one of these cycles. This allows vehicles that may have been caught in congestion a chance to find a new path given the network conditions.

3. Building the Hybrid Model

This section describes the extent of the hybrid traffic simulation model of the Twin Cities metropolitan region. The description begins with the presentation of the details pertaining to the development and preliminary calibration of the microscopic portions of the network surrounding the two light rail transit (LRT) corridors and proceeds outwards geographically to describe the greater network model in mesoscopic resolution. The implementation of traffic control (namely signalized intersections) and demand data are then described. The chapter concludes with an outline of the integration with the CUBE Voyager RPM.

3.1 Geometry

Several versions of the RPM exist to represent various "build" states of the network. In this case, two models are of interest: the 2009 and 2015 versions, representing the network before and after the construction of the Green Line, respectively. Both years were developed based on the 2000 10-year travel behavior inventory and have incremental adjustments implemented reflecting changes in network geometry as well as standard growth factors. Since the RPM is a macroscopic model, the detail required for microscopic simulation was not present within the core regions of the network which were the target for this investigation. To rectify this, two major regions were selected for manual improvement (see Figure 2). Region "A" includes the majority of the Blue Line light rail alignment along Hiawatha Avenue, as well as downtown Minneapolis and surrounding neighborhoods within Minneapolis between Interstate-35W, Minnesota Highway 62, and the Mississippi River. Region "B" covers the alignment of the Green Line, following University Avenue between the Minneapolis and Saint Paul downtown districts, and neighborhoods on both the north and south sides to include major parallel routes, especially Interstate-94. These two regions were developed concurrently in order to reduce the computational requirements for microscopic simulation and allow two engineers to calibrate separate microscopic simulation areas.

To create the microscopic network surrounding the light rail corridors, the existing roadways within the RPM were imported into Aimsun. The RPM within the Cube framework is a "stick" network containing curvilinear links and nodes representing all freeways, most arterials, and only major collectors throughout the Twin Cities greater metropolitan area. This provided a starting point with many of the roads already in place and connected in a reasonable way (although not perfect and lacking control). Additional roads (3000 sections) were added to complete the microscopic region of the network, including some road stubs (4000+) to represent important driveways, parking ramps, etc. where vehicles access the roadway. These additions were made by laying the network over aerial imagery of the region (taken from a Metropolitan Council photographic survey of the state).

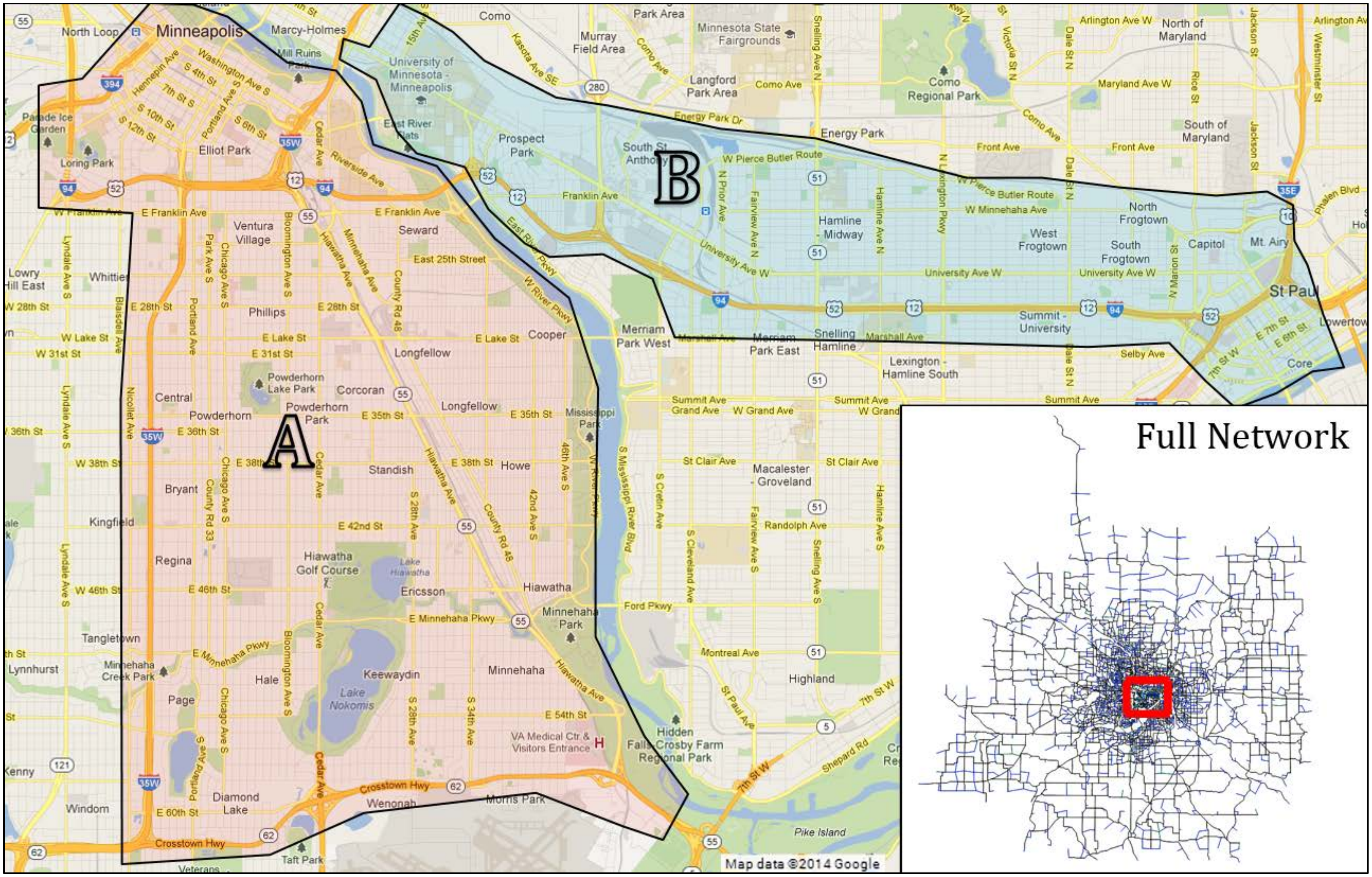


Figure 2. High-resolution core regions of the hybrid simulation covering the Blue Line (A) and Green Line (B); inset, the full extent of the Regional Planning Model network with the expanded region highlighted.

All existing roadway sections were also checked against these aerial photos to ensure geometric correctness. Once all the roads were imported or created, road types and speed limits were assigned to each section.

As described previously the two regions in Figure 2 were enhanced to include all arterials, most collectors, as well as some side streets, and appropriate intersection curvature. The total number of links within each area approximately doubled, with a significant increase in number of intersections. Figure 3 shows the original and improved Blue Line regions.

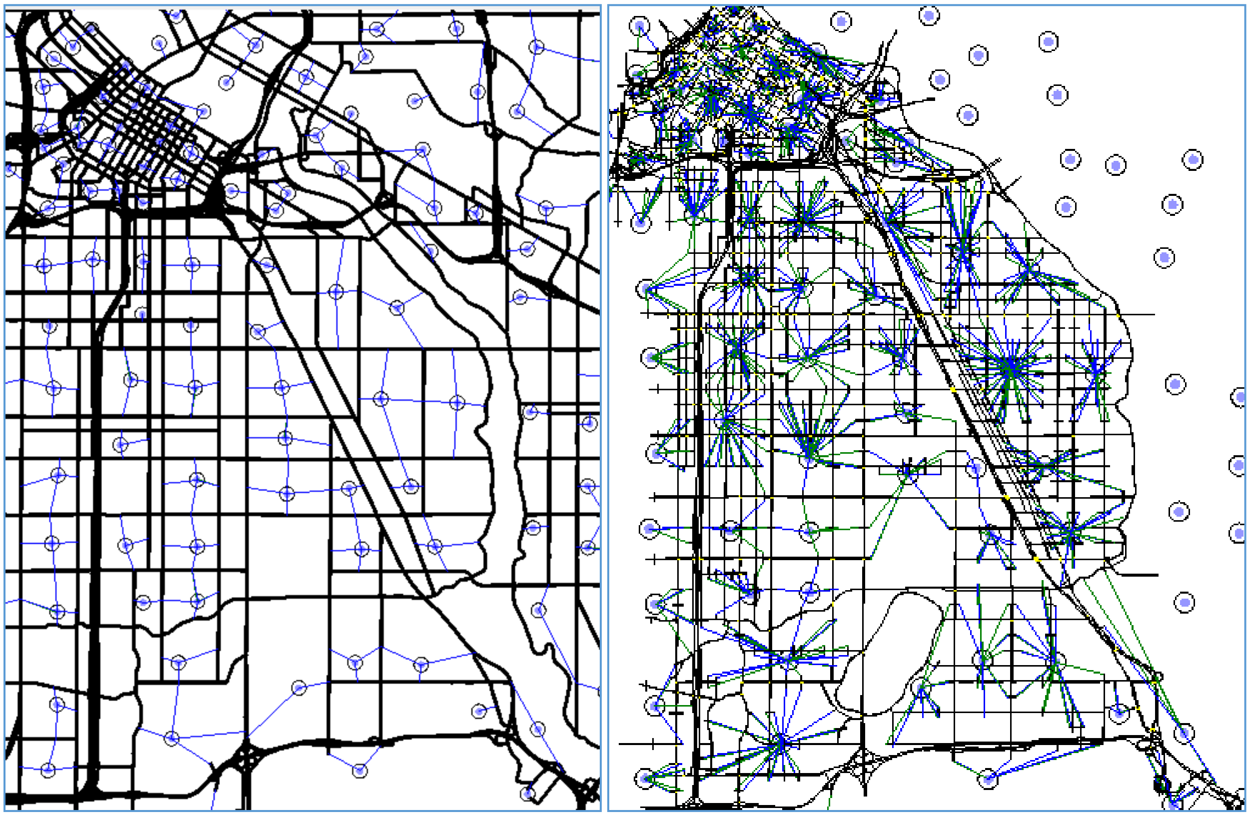


Figure 3. Original (left) v. improved (right) geometry of the Blue Line corridor.

Figure 3 also includes an important change related to the demand. Each small circle is a centroid, or origin/destination point, and the connections between centroids and surrounding roadways are collector-distributor links which load vehicles onto the network. In the original RPM, these centroids were connected only a few times to the relatively sparse network, offering vehicles few entrance and egress options. The increased resolution for microscopic simulation enabled these centroids to be connected to many locations in their respective zones in a more realistic way; vehicles no longer appear in the middle of arterial highways or multi-lane intersections.

Beyond adding roadways, improvements were made to turning geometries within intersections. By default, the Aimsun importer generated straight-line or simplistic curves for all turning movements within each node. Often, these connections did not capture real-world turning paths, turn bays, or appropriate yielding locations. Aerial and Google Street-View imagery were employed to correct these discrepancies. Within downtown regions, additional short right turn bays were added to reflect the real-world behavior of drivers who use street shoulders, parking areas, or bus stops to move past through-movement drivers when possible.

Alongside improvements to the road network, the light rail lines were integrated into the hybrid model's geometry. Two versions were developed: one representing the 2009 pre-Green Line network state, the other representing the 2015 post-Green Line state. As the Green Line is entirely encapsulated within the microscopic portion of the model, the outer regions imported from the RPM remained unaltered.

Implementing geometry was a significant startup cost in terms of hours of labor. Since generally only one individual could work on the model at a time, development occurred over the course of several years, with roughly a year and half of full time effort required for complete implementation and improvement. Table 1 summarizes link and node statistics describing the scope of the network.

Table 1. General network geometry information.

Links:	**Count**	**Length (Lane-Miles)**	**Length (Lane-Kilometers)**
Freeway Network	4570	4121	6633
Arterial Network	14780	12156	19564
Total	*19350*	*16278*	*26196*
Nodes:			
Intersection Nodes	8403	Centroid Nodes	1632

The final Aimsun microscopic Blue Line (Hiawatha) network (Figure 4) encompasses the Blue (Hiawatha LRT) line, downtown Minneapolis, and the southern portion of Minneapolis lying east of I-35W while north of Hwy 62. The Green Line (Formally the Central Corridor LRT) Aimsun network (Figure 5) includes portions of Minneapolis and St. Paul east of the Mississippi River that interact with the Green (CCLRT) line, including Washington Avenue, University Avenue, and downtown St. Paul.

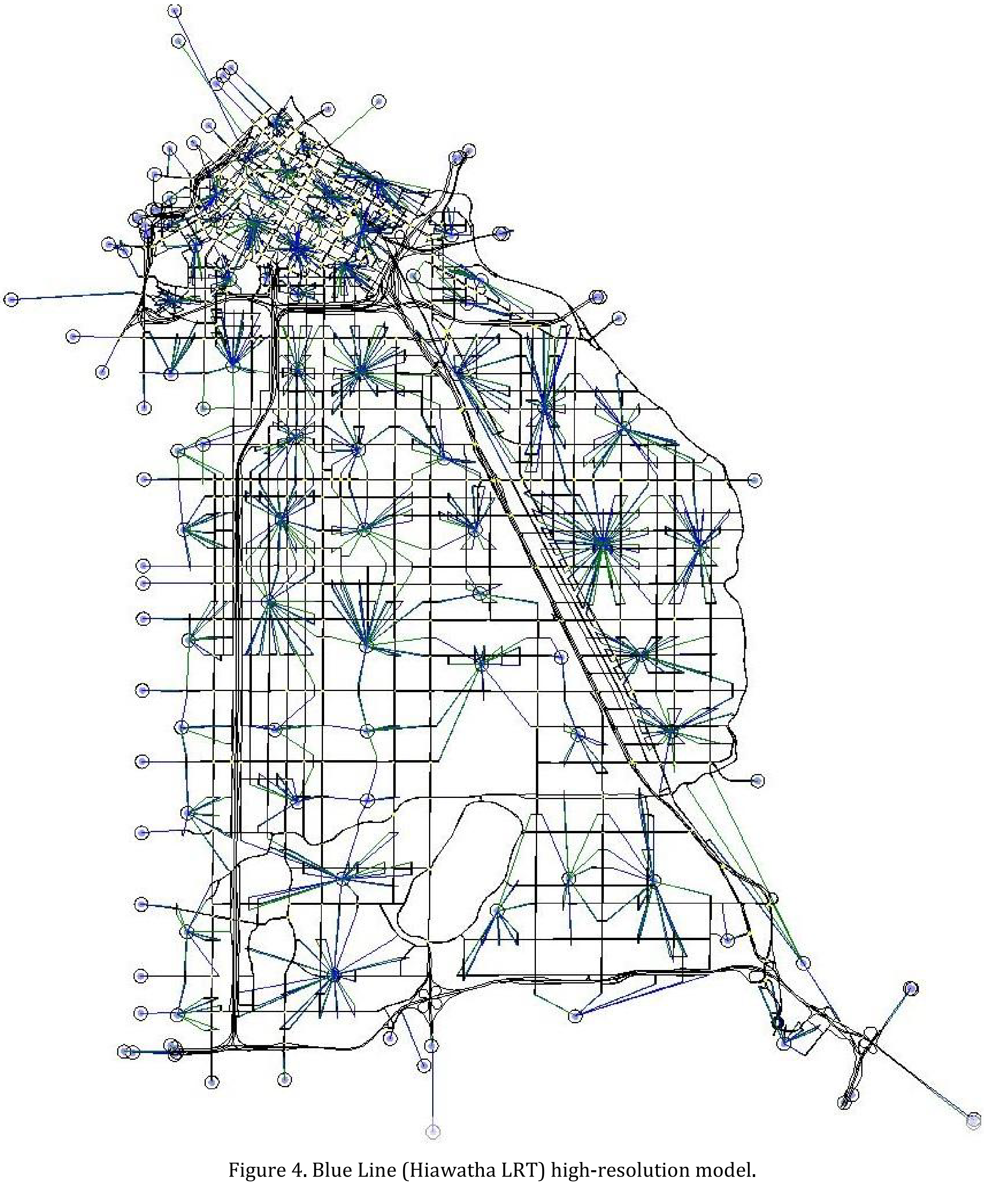


Figure 4. Blue Line (Hiawatha LRT) high-resolution model.

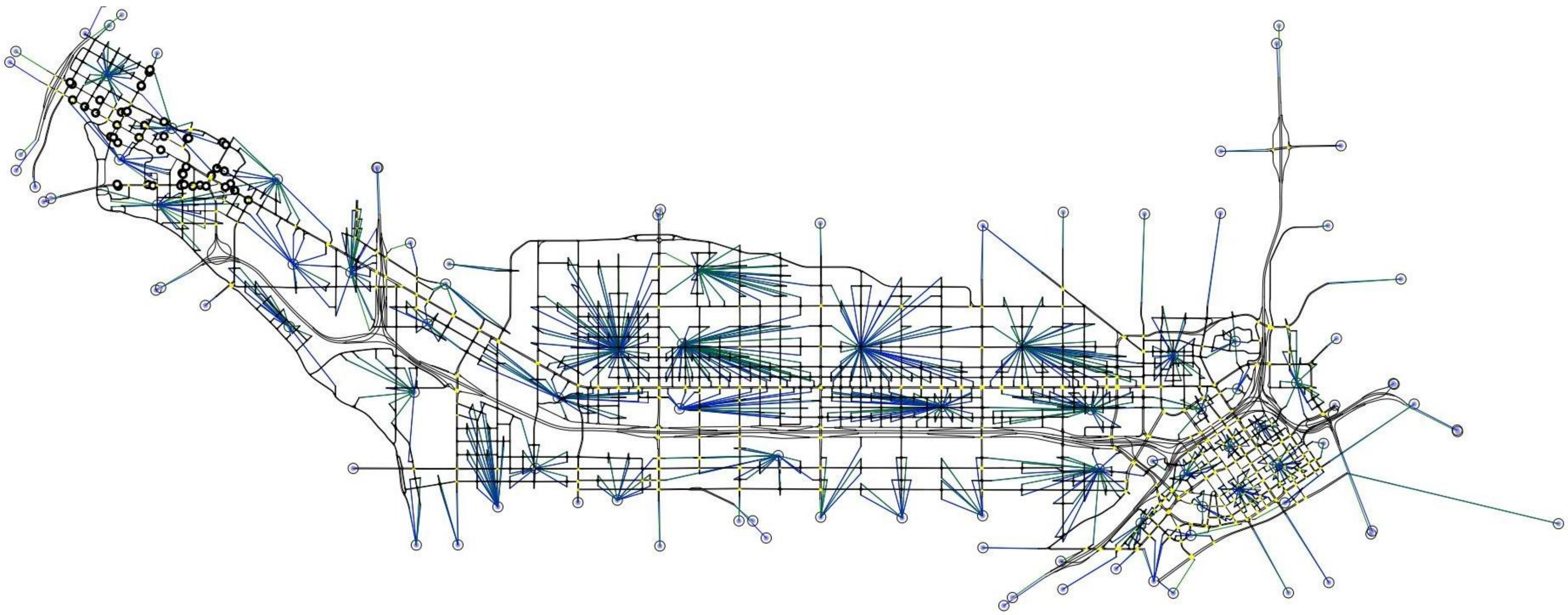


Figure 5. Green Line (CCLRT) high-resolution model.

Merging the two microscopic networks together, which were separated by the Mississippi River, primarily involved stitching river and highway crossings together. Stitching the combined microscopic network with the Voyager macroscopic model involved stitching thousands of links together. A cutout version of a direct import from Voyager is used as the base network, in which all sections that were present in the Aimsun microscopic network were manually removed from the Voyager import to aid the stitching process. In cases of uncertainty, roads were not removed out of caution and were compared directly to the microscopic network after importation. Figure 6 shows a partial view of the Voyager network with the two micro networks stitched in.

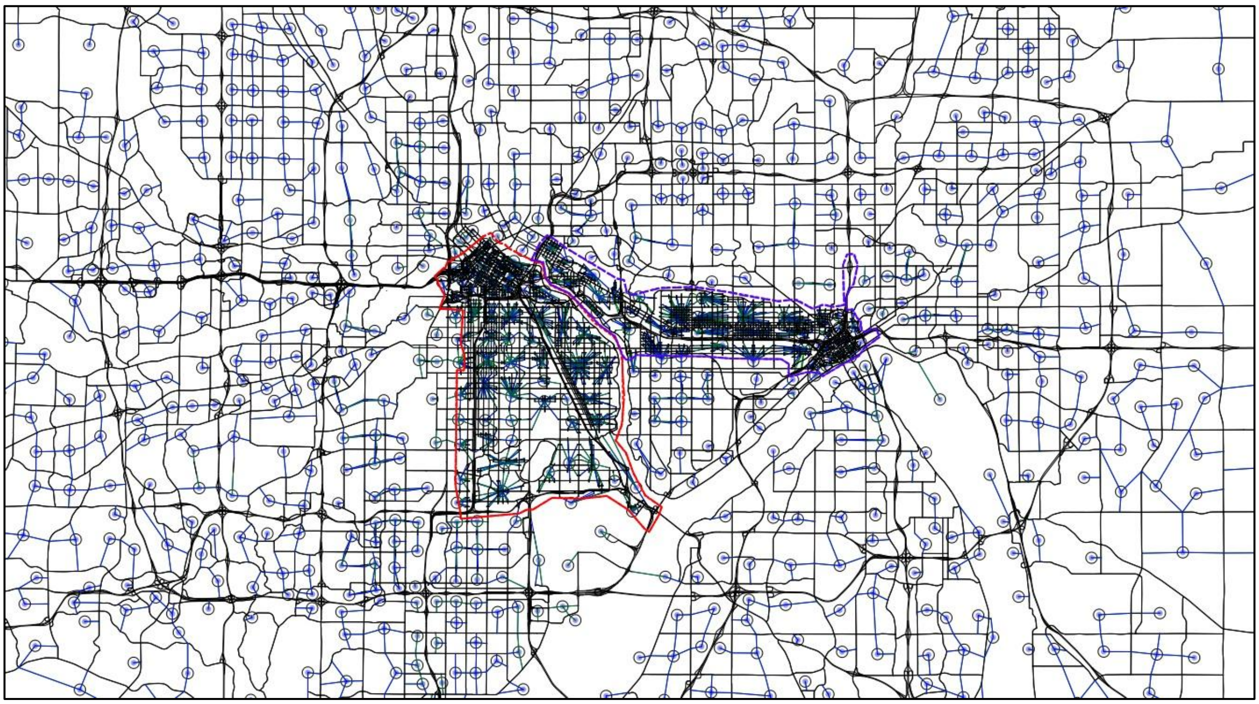


Figure 6. Twin Cities Metropolitan hybrid simulation model (partial picture).

An issue that arose during the stitching process was how to reconnect the thousands of centroid connectors to links in there corresponding Traffic Analysis Zone. While this could have been done manually it was a tedious and time consuming process that would take several days to complete. Consideration was also given to the fact that if this process would have to be done again a more stream lined approach would be needed. There for a script was designed to connect the centroids to the ends of links that were not connected to a node based on their name. By giving all sections that needed to be connect a specific formatted name corresponding to the centroid that need to be connected a script could easily attach the thousands of links in seconds. This process took only half the time and minimized errors that would have been otherwise caused by the manual linking. The script can be found in the appendix.

A full network check, using the microscopic network checker in Aimsun, was run with demand matrices in order to locate unstitched link ends. After Aimsun completed locating the unstitched links, these were fixed manually. The microscopic simulation network checker found several hundred errors related to low turning speeds and other geometric issues. In the areas outside the microscopic sections these can be ignored due to the fact that they will be modeled at the meso-rough level. It was, however, useful to find centroids that were not connected and sections that ended but were not connected to a centroid or a node. Voyager as an application is not affected by such unfinished elements but Aimsun does not allow them.

3.1.1 GREEN LINE-SPECIFIC ADJUSTMENTS

Significant changes occurred geometrically along the entirety of the Green Line as the rails often replaced existing roadway. Center lanes were removed along much of Washington and University Avenues, especially dedicated left turn and right turn pocket lanes at intersections. Within the University of Minnesota, Washington Avenue was converted from two-lane-each-way general purpose segments to one-lane-each-way bus/emergency-vehicle-only lanes. The intersections at Church and Union Streets were similarly altered and crossing general purpose lanes were completely removed. The signals for these two intersections were retained to allow for pedestrian/bicycle crossing actuations. Vehicles are diverted to East River Road along the Mississippi River or slightly to the east along Harvard Street (which only allows north-south crossings of Washington Avenue). Finally, Walnut street was converted from a typical 4-way intersection to a 3-way general purpose intersection with bus-only single lane approaches on the west side (one entering the intersection eastbound, one leaving westbound).

Outside of the University area, 23 intersections between the Green Line path and smaller crossing arterials were bisected leaving two T-intersections (right-in, right-out). A full list of these locations is included in Table 2 while Figure 7 and Figure 8 below show examples of these changes near Snelling Avenue.

Table 2. List of intersections converted from 4-way to T-intersection pairs.

Arthur Ave SE	Beacon Ave	N Oxford St
30th Ave SE	N Wheeler St	N Milton St
Emerald St SE	N Pierce St	N Avon St
Curfew St	N Simpson St	St Albans St N
Carleton St	N Albert St	N Kent St
Montgomery St	N Syndicate St	Arundel St
Lynnhurst Ave	N Dunlap St	N Farrington St
Crossing for Episcopal Homes parking, just west of Fairview Avenue		Galtier St

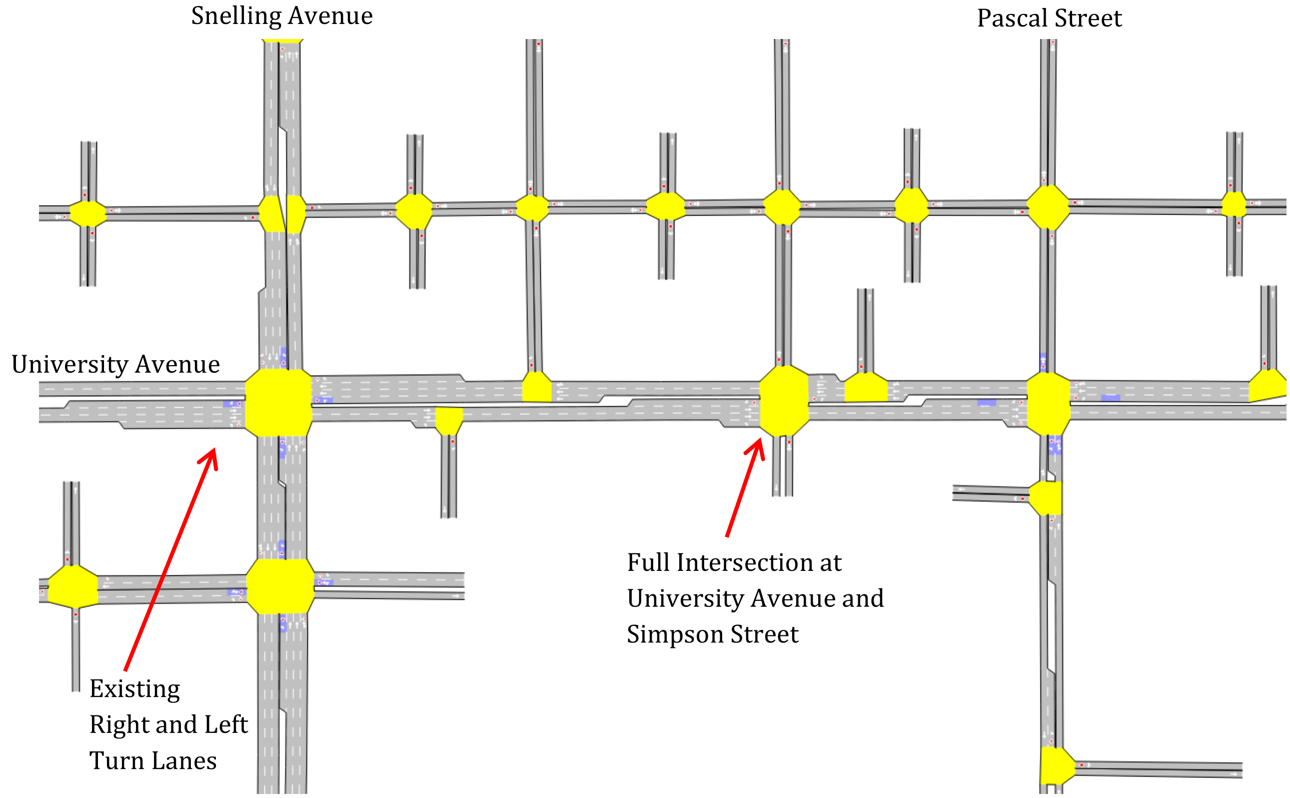


Figure 7. Region near Snelling Avenue and University Avenue - Pre-LRT

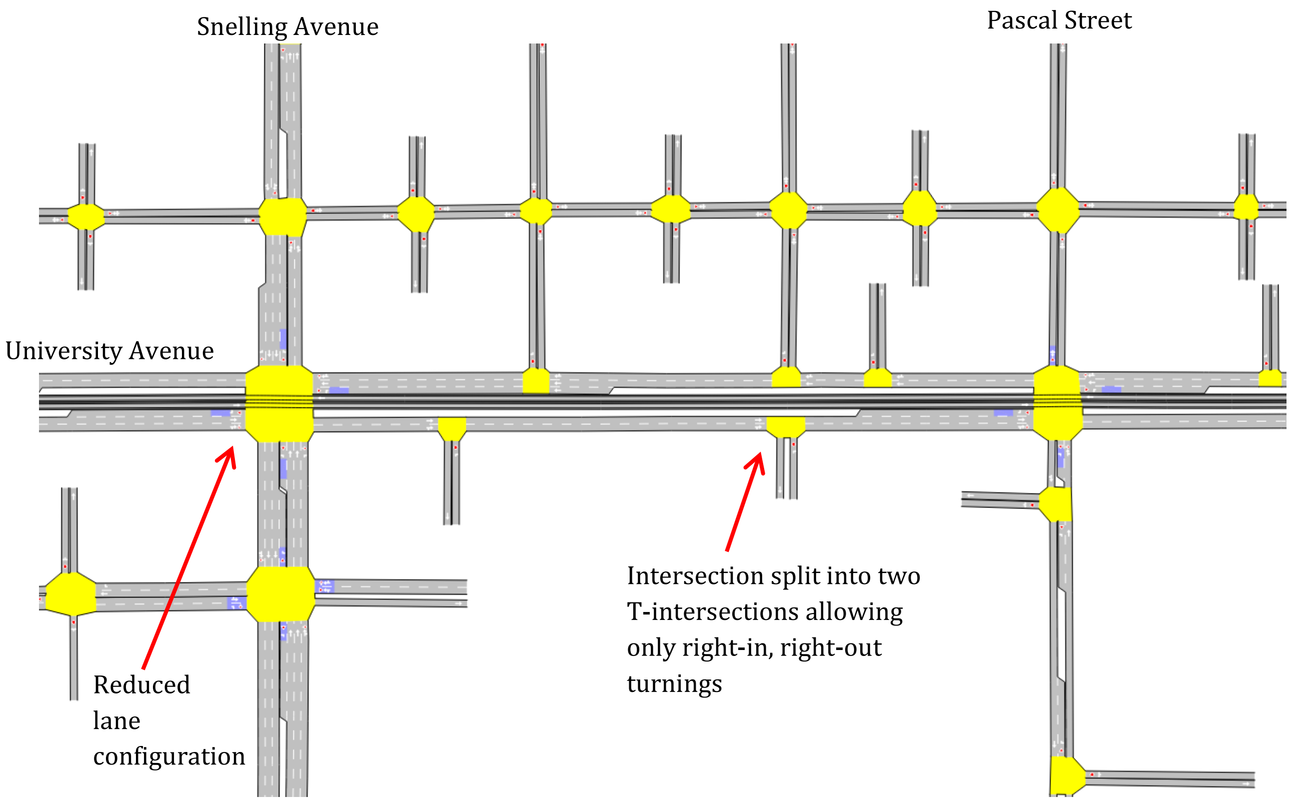


Figure 8. Region near Snelling Avenue and University Avenue - Post-LRT

3.2 Signal Control Implementation

For the individual microscopic networks, there were three control plans: AM, PM, and off-peak. When the two microscopic networks were combined, a master control plan was created that calls for all six plans to be run at the specified time intervals alongside one another (Figure 9). This implementation is considered to be successful as no issues have been detected due to the microscopic control plans being called upon by the master control plan. A detailed explanation of the steps taken to implement the controls was included in the deliverable for Task 3 and therefore is not covered in this report.

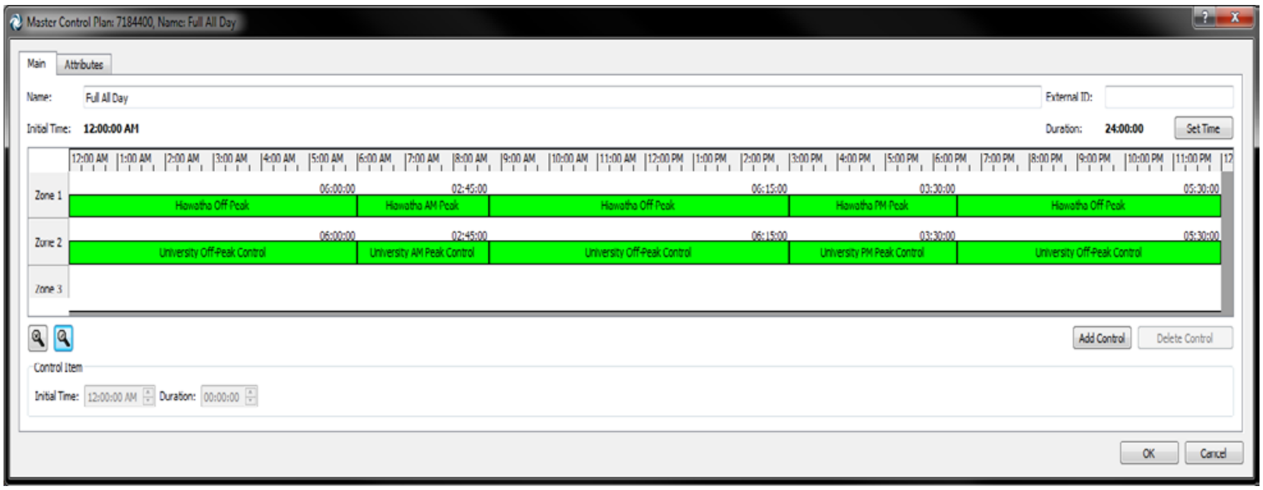


Figure 9. Master Control Plan timetable.

After the new signal timings for the Green Line were acquired they were implemented into Aimsun along with the new geometry. The signals were very similar, as far as implementation, to other signals in the region. Only a few of the Green Line lights were listed as preemption while the rest were considered to be LRT Priority where any extra green time was given to the LRT Phase. Table 3 contains the changes between the before and after corridor implementation.

Table 3. Control statistics including Before/After Green line.

	COUNT BY REGION		
Control Type:	**Blue Line**	**Green Line Before**	**Reprogrammed for Green Line**
Fixed	318	96	26
Semi-Actuated	92	114	25
Fully Actuated	13	8	4
LRT Preemption	8	-	8
LRT Priority	-	-	29

The plans implemented were produced by a consulting firm for the corridor and were the best possible place to start from. During the final months of the project (after the opening of the Green Line) it was found through field observations and discussions with local city engineers that the original timings have been significantly altered to meet operational needs on the ground. This mirrors alterations which were made to the Blue line following real-world implementation. These alterations were not included in the model since they were not finalized before the end of the project.

3.3 Demand Implementation

The original Blue and Green Line microscopic networks were simulated using traversal matrices extracted from the RPM. The new greater metropolitan hybrid model incorporates every centroid from the Voyager RPM, meaning that all of the demand matrices were imported exactly as they appeared in the RPM with no reductions or major modifications. One modification was made to the imported matrixes regarding inter-TAZ trips. Voyager included in the demand matrices trips from each centroid to itself; these trips do not participate in the traffic assignment process but are included in Voyager for completeness. In Aimsun, where each trip represents an actual vehicle, this resulted in vehicles entering the network, following a short path back to the same centroid, and exiting again. These short trips caused unrealistic congestion surrounding some centroids. They were removed by eliminating the diagonal elements in each O/D matrix during importation.

When the two LRT region models were incorporated into the single full hybrid model, an issue was discovered regarding centroid importation. Each imported centroid configuration would properly incorporate the centroid locations but not centroid connections. Scripts were developed to automatically capture and replace these connections within each network, thus saving significant manual effort within the tedious graphical interface.

With centroids and connectors in place, vehicles are able to enter, traverse, and exit the network. However a decision on the arrival pattern had to be chosen for how, and what rate, vehicles would enter the network. For each demand interval, it was chosen for Aimsun to assume vehicles enter the network at a constant rate based on the total interval volume. However, as the simulated periods for this analysis include peak period times, flat entrance rates do not adequately describe entering volumes. To compensate for this, each demand interval was broken into smaller components; in this case, the 45-minute or 1-hour demand periods were split into 15-minute increments. The total period volume was then split across each 15-minute increment using adjustment factors to smooth entrances across the entire time window being analyzed.

These factors were chosen based on an examination of multiple freeway sections from around the Twin Cities metropolitan area with detectors that did not exhibit 'abnormal' behavior. The term 'abnormal' in this case is defined as a section that did not break down due too extraneous situations such as road construction, difficult geometry, or other issues that would affect the flow of a section. Therefore a 'Normal' section was one that was found to have steady flowing traffic even if that sections speed was not free flow. Once these sections were identified, the shape of the flow curve was normalized between all the different sections to produce a flow curve for 24 hours. That curve was used as a general representation of the fluctuations of demand in the Twin Cites region.

The flow curve described was used in conjunction with an excel bar chart of all the demand intervals cut into 15 minute segments. These segments were then altered by whole percentages to match the shape of the curve through visual inspection. The percentages were consistently checked to ensure that the total demand over the entire original demand interval did not exceed 100%. Since the overall all demand in the time period stays the same it was found that this method created more realistic results than the other default arrival patterns available in Aimsun (such as Exponential, Uniform or Normal). This process is illustrated by Table 4, which shows the demand volumes and adjustment factors, and Figure 10, which shows the entrance rates per 15-minute interval for the original and adjusted demand curves for the periods covering morning peak (periods 6 through 10).

Table 4. Demand adjustment factors used to smooth vehicle entrances.

Start time [hr:min]	Percentage given [%]	Total for region [%]	Start time [hr:min]	Percentage given [%]	Total for region [%]	Start time [hr:min]	Percentage given [%]	Total for region [%]	Start time [hr:min]	Percentage given [%]	Total for region [%]
0:00	100		9:30	28		14:30	22		19:00	30	
2:00	100		9:45	23		14:45	25		19:15	26	
3:00	100		10:00	24	100	15:00	26	100	19:30	22	100
4:00	100		10:15	25		15:15	27		19:45	22	
5:00	100		10:30	25		15:30	23		20:00	30	
6:00	20		10:45	20		15:45	24		20:15	26	
6:15	30	100	11:00	25	100	16:00	26	100	20:30	22	100
6:30	50		11:15	30		16:15	27		20:45	22	
6:45	23		11:30	23		16:30	22		21:00	30	
7:00	32	100	11:45	24		16:45	23		21:15	26	
7:15	45		12:00	28	100	17:00	25	100	21:30	22	100
7:30	40		12:15	25		17:15	30		21:45	22	
7:45	30		12:30	27		17:30	60		22:00	35	
8:00	20	100	12:45	26		17:45	40	100	22:15	25	
8:15	10		13:00	25	100	18:00	35		22:30	20	100
8:30	22		13:15	22		18:15	25		22:45	20	
8:45	23		13:30	21		18:30	20	100	23:00	100	
9:00	27	100	13:45	20		18:45	20				
9:15	28		14:00	25	100						
			14:15	34							

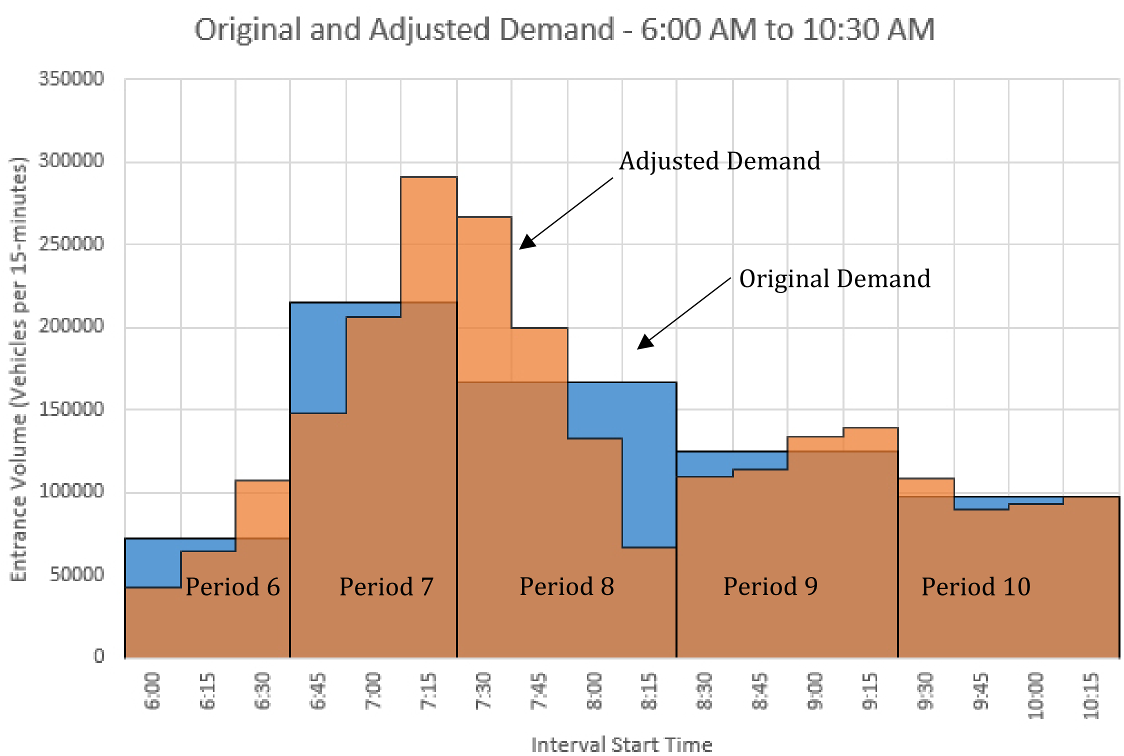


Figure 10. Original and smoothed demand for the morning periods.

3.4 Integration with Voyager

A main objective of the project was to integrate the hybrid simulation traffic assignment results with Voyager's 4-step travel demand modeling process. Specifically, the approach to this integration will be to form a loop between the Aimsun and Voyager models. Starting with the Voyager full travel demand modeling process, a first set of O/D matrices are produced and imported into the Aimsun hybrid simulation model to support a dynamic traffic assignment process. This DTA simulation produces link travel times and average speeds for the whole network. These travel times are then imported back into Voyager's Mode Choice modules to produce a new set of demands (i.e. O/D matrices). The process is then repeated until the O/D matrices produced between two steps are sufficiently similar.

Figure 11 shows the two different loops. The first loop (Step A) is the current 4-step model in use by the Metropolitan Council in the RPM. The second loop (step B) describes the loop performed between the Aimsun-based hybrid model and the Voyager-based RPM.

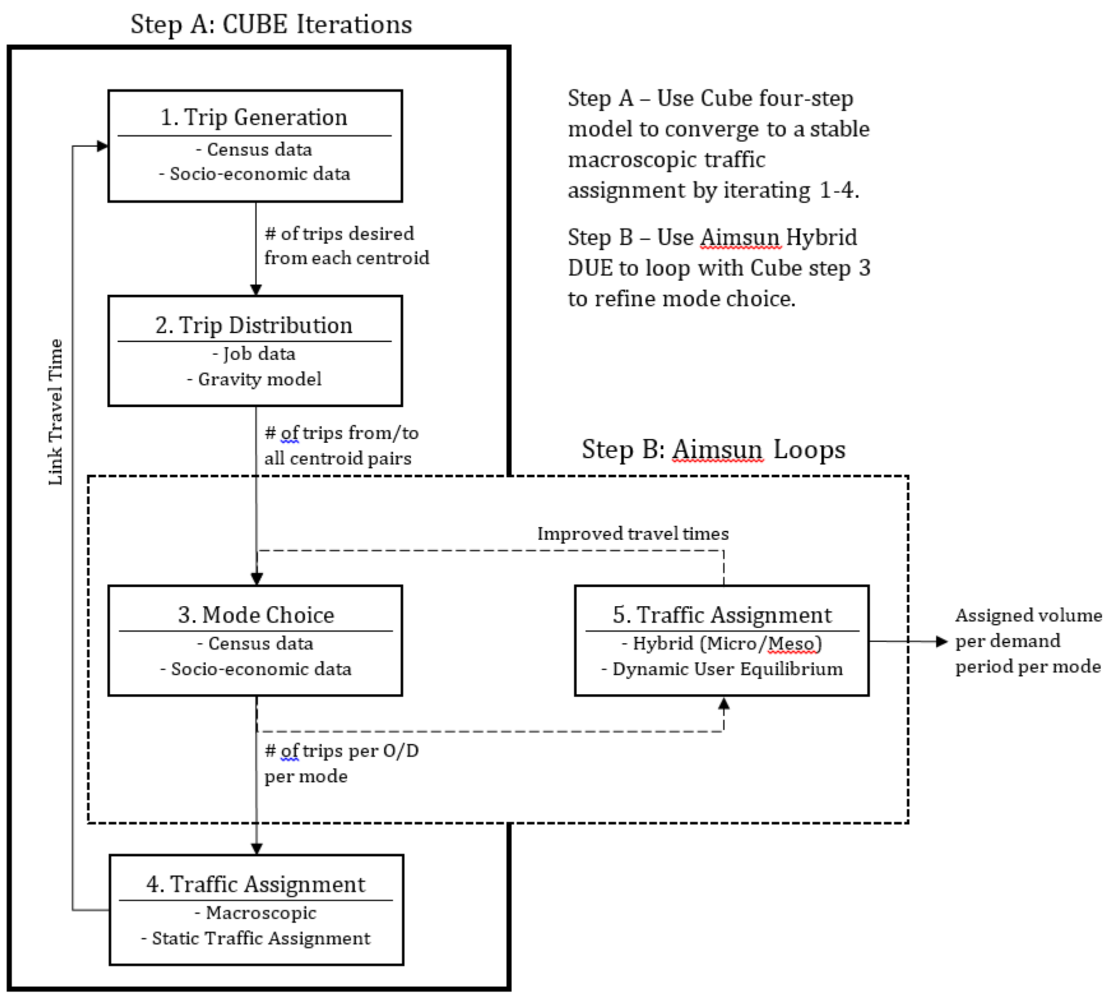


Figure 11. Flow diagram for Voyager-Aimsun loop.

Before the loop could proceed, a linkage had to be made to pass information between the two simulation environments. Since Voyager is based on a "stick" network, each Voyager link can be uniquely identified using either a link ID or the origin and destination nodes (in this case, node refers to simple intersection locations and not centroid nodes). However, between different versions of the RPM each link is reassigned unique link ID values. Only the origin-destination node IDs remain fixed (although changes to the network that add or remove nodes do obviously necessitate some local alterations). Between the two model versions of interest for this investigation (the 2009 and 2015 RPM models), no node changes were made which would impact the region of interest (minor node changes were at the outskirts of the mesoscopic region).

Within Aimsun similar issues were encountered. Like Voyager, every link has an ID and, in most cases, numerous attributes imported from Voyager. As described in earlier sections, when the microscopic portions of the network were improved, for reasons of accuracy and realism, many additional links were introduced, while most of the Voyager links in the Blue/Green Line regions were broken into smaller sections to better match real world geometry and incorporate additional minor intersections. These new and adjusted links within Aimsun lack information tying them to the Voyager network. To complete the connection back to Voyager, this information was redeveloped. However, since the Aimsun model includes more roadways than the RPM (and potentially multiple sections corresponding to one RPM link) and because each model includes tens of thousands of links an automated method of generating link mapping tables was created using ArcMap.

Within ArcMap, the Spatial Join tool along with some careful assumptions allow for this mapping to take place. From Aimsun, both the RPM macroscopic network links and the Aimsun microscopic network sections were exported to GIS. The Aimsun export function created two files of interest for each network, "section.shp" and "sectionGeo.shp", each of which was added to ArcMap. The section.shp file contains information regarding section properties as defined within Aimsun (such as ID, speed, capacity, etc.) while the sectionGeo.shp file contains information regarding the geometric layout of sections (coordinates of vertices, lane configurations, etc.). To clearly differentiate between the RPM links and Aimsun links, the shape files were renamed (Figure 12).

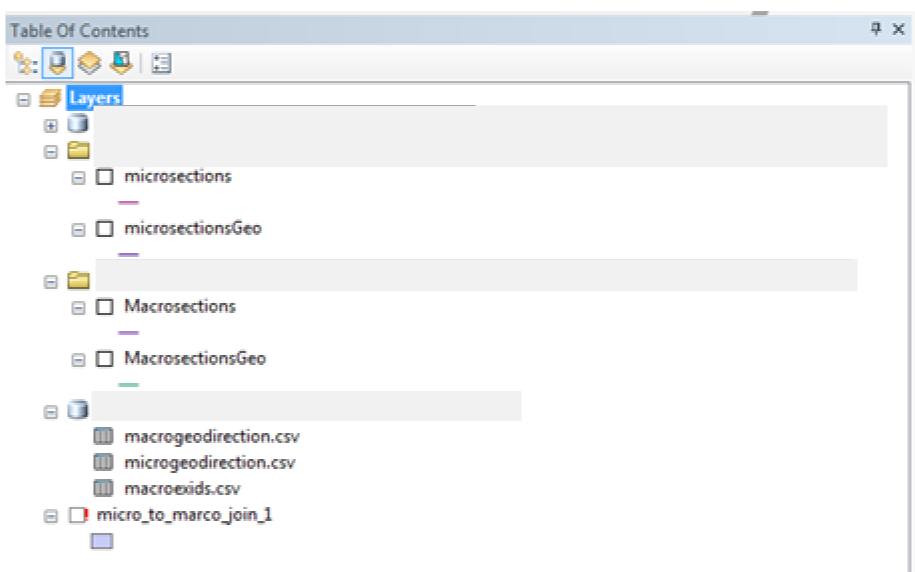


Figure 12. GIS layers involved in Aimsun – Voyager integration.

Once both networks were within ArcMap, the Spatial Join tool was used to find overlapping links. Because the Aimsun model contains many shorter segments that each belong to the same RPM link, the spatial join mapped the RPM information onto the Aimsun links so that each Aimsun link would be assigned to only a single RPM link.

For the spatial join to work properly, each link in Aimsun was transformed into a point at the center of each section. These points were then given successively increasing radii to produce circles between 2 and 90 meters in diameter. By using a series of expanding circles, Aimsun links which lie near their RPM counterpart are able to locate a match quickly without intersecting multiple possible partners while more distant pairs are still able to locate a partner eventually.

However, because the RPM links for opposing directions along a single roadway fall directly on top of one another in many cases, the bearing for each link was calculated and used to further winnow out bad matches. Within the GIS framework, the geometric properties of both Aimsun and RPM model links were available for analysis. Figure 13 below shows a sample section and the information contained within the sectionGeo.shp file that is relevant to generating a bearing for the Aimsun sections (similar information was used for the RPM links). The coordinate pairs (fx, fy) and (tx, ty) represent the centers of the "from" and "to" ends of each section. Using an Excel script, these coordinates were compared for each section and a general bearing was calculated.

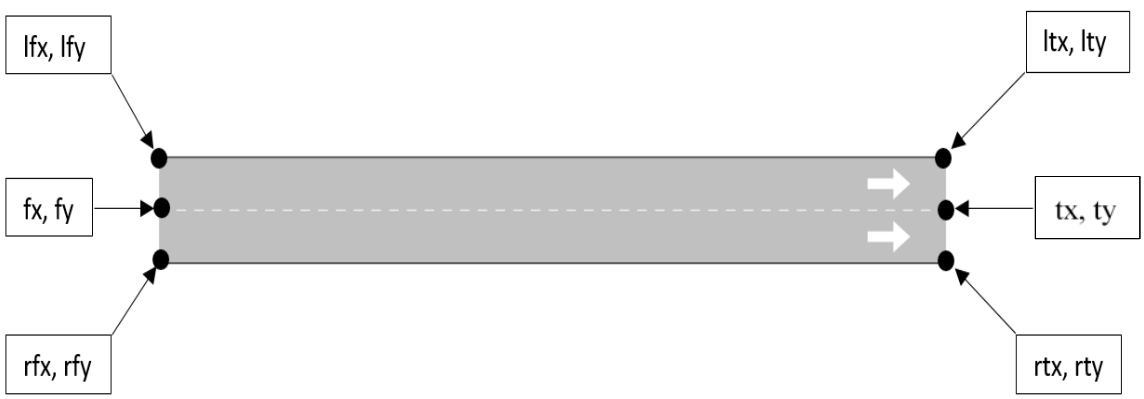


Figure 13. Section geometry parameters used in Aimsun.

From the Spatial Join tool, a database was created which contained all possible partner sections for each Aimsun link. These were then narrowed to those with matching bearings (within 5°) and the best matches available were kept. The remaining links without good matches were examined manually.

The following steps cover the entire process:

1. Export Aimsun links and RPM links from Aimsun to GIS shapefiles
2. Import section.shp and sectionGeo.shp for each model into ArcMap
3. Prepare information for spatial joins
    a. Join relevant information from sectionGeo into section for each model
    b. Add bearing for each link
    c. Convert Aimsun sections to points, then add buffer radii
4. Use Spatial Join tool on each set of buffers
5. Output results into database
6. Filter results based on best matches and bearing

This process results in the update of the main hybrid simulation model with the extra information establishing the link with Voyager. Following the completion of a successful simulation, a custom script produces a text file that contains all links that exist in both models. The file has the following information for each link.

1. Aimsun ID
2. Voyager ID
3. Average Speed

This file is imported into an Access database and the records are consolidated to result in one, and only one, instance of a Voyager link. This is necessary because as already described there can be more than one Aimsun link corresponding to a single Voyager one. The result is a table containing all Voyager links with an average speed representing the average over all Aimsun links each Voyager link belongs to. A final relationship is established between the average speed table and the GIS table of the original RPM and the information regarding the A and B nodes of each link is combined as well as calculate the Travel Time for each link based on the Aimsun speed and the link length from Voyager. This last step allows the integration of the speeds with any subsequent version of the RPM that has not made any changes in the geometry.

3.5 Scenarios for New Mode Choice Result

During the integration with Voyager several experiments were set up in order to capture the effects of the change in mode choice that occurs due to the higher resolution of the hybrid model. As was seen in Figure 11 the integration with Voyager did not incorporate the entire 4 step model and therefore the only needed parameters from the Hybrid model were the average speed on each link. However due to the structure of the regional planning model only the speed for certain periods were needed for mode choice to be run and those periods were Demands 7 – 14 (6:45 – 14:30).

The original plan and proper execution of the model was to use the three different types of simulation, macroscopic, mesoscopic, and Hybrid, to arrive at the final speeds to be input into voyager. The first step was to run a macroscopic simulation of each demand interval and save the origin to destination paths from each one. These paths were then to be used as an initial "starting" point for the Mesoscopic DUE model so that it could reach convergence faster. The output of the Mesoscopic model would again be paths but this time since they came from a Mesoscopic model they would be time dependent and more detailed than the macro set. These Mesoscopic paths were then to be used as an input to the Hybrid model. The thought for using the mesoscopic paths in the hybrid model was to account for the so called historical paths of the day to day users who were unlikely to radically shift their route in order to avoid congestion. These paths were to be used by 60% of the vehicles in the network. The other 40% would be split in half and would start pick a path when they entered the network based on its conditions and would then stick to it for the remaining time. The remaining half would also pick a path based on the network conditions but would be able to reroute or chose a new path every 7.5 minutes.

This method was to be conducted for the 8 demand intervals, seen in Table 5 along with run statistics, and the aggregated average speed of each link from each interval would be read into the mode choice model. The mode choice model would then produce origin destination (OD) matrices for the Aimsun models to be run again. This loop was to be done until no relevant change in demand could be seen.

Unfortunately due to the computational requirements and simulation time need for each loop this was found to be infeasible in the constraints of this project. Therefore the loop was shortened so that only one simulation was run in Aimsun and only two different file transfers had to occur. The solution and the way we avoided inaccuracies in the model results, was to run a Hybrid Dynamic User Equilibrium (DUE) for each demand interval. Since the Hybrid DUE was run directly and only the statistics of the sections need to be saved in order to produce relevant speeds and all other outputs could be turned off to save computational time and memory requirements. This produce a simple loop as seen in Figure 14 which only required some manual intermediate steps involving Access to clean and write the data into a form that Voyager could use. The process though can be completely streamlined to require no manual intervention.

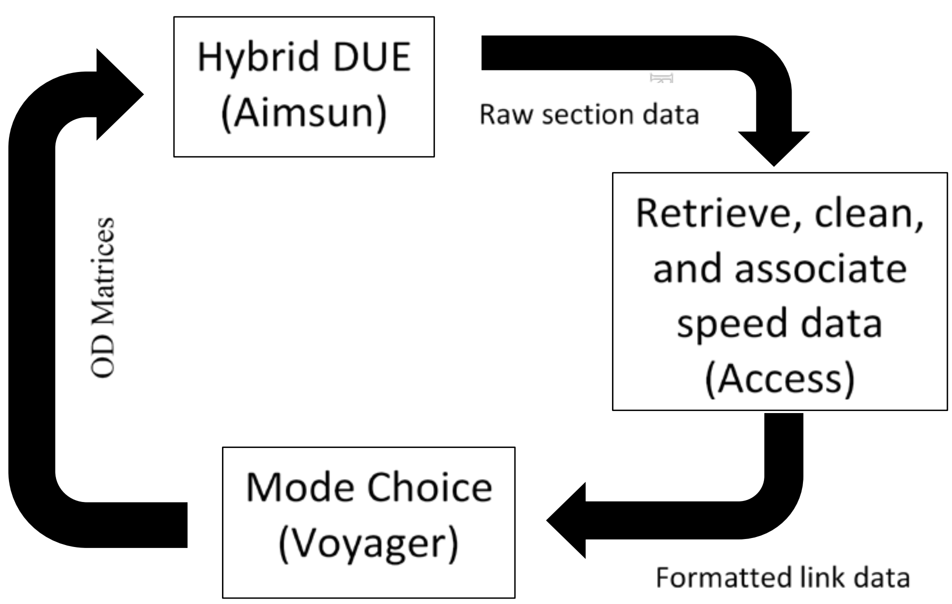


Figure 14. Flow diagram for passing data between Aimsun and Voyager.

Table 5. Simulation time and vehicle demand for iterating through mode choice.

Demand Interval	Time	Duration Seconds	Duration Hours	Vehicle Demand
7	6:45 – 7:30	25,983	7.2	773,514
8	7:30 – 8:30	74,078	20.6	781,017
9	8:30 – 9:30	31,844	8.9	568,583
10	9:30 – 10:30	23,883	6.6	438,598
11	10:30 – 11:30	45,436	12.6	518,001
12	11:30 – 12:30	34,566	9.6	592,584
13	12:30 – 13:30	38,498	10.7	550,895
14	13:30 – 14:30	10,934	3.0	394,901

3.6 Before and After Green Line Scenarios

The scenarios that were to be used to analyze the before and after impact of the green line on the neighboring roads were going to be similar to the mode choice loop. The initial plan was to do exactly what was described in the previous section except that there would be two networks from which the entire process would be run. The networks would be a before network which would represent the network if the green line had never been implemented and the after network which represents the geometric and signal changes caused by only the implementation of the light rail. The main difference is that there was no loop with Voyager and no change in demand. The peak periods were simulated and compared against each other to see the changes in the network.

Again the computational and time requirements of the model prevented the use of the more proper scenario technique. Therefore the model was again reduced down to a single DUE run for each of the demand periods during peak period in each model. Table 6 shows a list of the completed runs and the time associated with each.

Table 6. Computational and time requirements for Green Line before-after single-period simulations.

		Pre Green Line Network			Green Line Network		
Demand Interval		**RAM (GB)**	**Iterations**	**Run Time (hr)**	**RAM (GB)**	**Iterations**	**Run Time (hr)**
6	6:00-6:45	17.5	4	1.6	24.2	5	1.7
7	6:45-7:30	49.5	13	4.3	55.5	14	7.1
8	7:30-8:30	116.6	24	20.5	88.7	19	14.0
15	14:30-15:30	65.1	13	8.8	70.1	13	9.9
16	15:30-16:30	125.1	25	19.1	85.1	16	14.9
17	16:30-17:30	118.0	25	21.9	148.1	25	22.5
18	17:30-18:00	38.0	16	7.2	40.2	14	9.2

These were the initial runs that were used to compare the two models. It was found later that a slightly different approach to the simulation showed more realistic results for the peak period. Therefore a new set of simulations focused on getting the best peak period results for demand 8 and demand 17. The simulations that were used were a combination of multiple demand intervals which required significantly more RAM and increased run times but resulted in fewer simulations to run (4 total vs 14). These runs are summarized in Table 7.

Table 7. Computational and time requirements for Green Line before-after 3-period simulations.

		Pre Green Line Network			Green Line Network		
Demand Intervals		**RAM (GB)**	**Iterations**	**Run Time (hr)**	**RAM (GB)**	**Iterations**	**Run Time (hr)**
6, 7, 8	6:00-8:30	291	27	92.2	261	26	86.1
16, 17, 18	15:30-18:00	356	27	114.14	331	25	78.7

It is important to note that the run times in the case of scenarios where the RAM used exceeded 256GB are not accurate because the computer had run out of memory and was using the drive for temporary storage. This technique allows a simulation to eventually finish, although it increases the run time tenfold. In a computer with more RAM the scenarios in the aforementioned table would have had considerably shorter run times.

4. Calibration

Throughout the development of the Aimsun hybrid model, calibration and validation efforts were undertaken to ensure the hybrid model would both align with the Regional Planning Model and also produce representative results according to real network data. Calibration within this framework refers to adjustments made to network or vehicle parameters which aimed to correct irregularities within simulated behavior. In many cases, calibration focused on identifying behavior which required no real data for comparison, such as identifying 'lost vehicles' – vehicles unable to reach their intended destination. Calibration measures were implemented at the local level (individual link or signal corrections) and, especially after the integration of the full hybrid model, at the regional level (links within certain areas or of certain types across the entire region).

Validation, on the other hand, refers to direct comparisons of simulated data, such as link speeds or flows, against data which are considered real (e.g., turning counts, loop detector data). At the macroscopic resolution, validation was carried out between the Aimsun model and the Regional Planning Model, using link volumes from the RPM as 'real' data. At the mesoscopic and microscopic levels, turning counts and freeway flow and density data were used.

4.1 Macroscopic Validation

As part of developing the link between Aimsun and Voyager, validation was performed to assess the compatibility between the two environments. Based on the network and demand matrices imported from Voyager, a verification process was implemented to show that Aimsun could produce results comparable to those of the calibrated Regional Planning Model in Voyager. This crucial step ensured that Aimsun's simulation methodologies were in line with the RPM and, by extension, the improved Aimsun model could produce results through mesoscopic, microscopic, and hybrid simulation which would appropriately reflect back to the results produced by the RPM.

For expediency, this process was completed for two sub-networks: the Green and Blue Line regions (University Avenue and Hiawatha corridors). Four main issues were identified and corrected as part of the validation process: self-centroid trips, unusual centroid configurations, Volume-Delay Functions, and HOV behavior.

4.1.1 SELF-CENTROID TRIPS

While Voyager allows demand matrices to contain entries from a centroid to itself, such trips are not used by the model to load the network. By contrast, Aimsun treats such trips as any other and creates vehicles, loads them into the network, and assigns a route. As such, vehicles traveling from a centroid back to itself must traverse some small distance in the network, causing loading which is unrealistic. This behavior difference was already known prior to implementing the hybrid model, so all diagonal entries in macroscopic demand were eliminated prior to the first macro static traffic assignment which is referred to as 'Step 1'.

4.1.2 UNUSUAL CENTROID CONFIGURATIONS

In certain locations within the RPM multiple centroids were connected to the same node. Within Voyager's framework, vehicles traveling between these two centroids treated the centroid connectors as their 'path' and never entered the road network proper. As with self-centroid trips, Aimsun forces vehicles to enter the road network and traverse some actual path before returning to a centroid connector. For such cases, additional stub links were created to handle vehicles between the two centroids either by providing them a short path at the edge of the road network or a completely isolated pair of 'floating links' which serve only vehicles between the centroid pair.

4.1.3 VOLUME-DELAY FUNCTION ADJUSTMENT

A main component of the RPM and the macroscopic model are the Volume Delay Functions (VDF's) that define sections. The VDF's (defined in the RPM by the Metropolitan Council) are based off the Spiess formula:

$$t = t_0\left(2 + \sqrt{\alpha^2(1-x)^2 + \beta^2} - \alpha(1-x) - \beta\right)$$

where:

t = average travel time per unit distance,

t_0 = free-flow travel time per unit distance,

x = v/c ratio, and

$\beta = \frac{2\alpha-1}{2\alpha-2}$, and α is a number greater than 1.

The VDF's were translated from the Voyager custom scripting language to Aimsun's syntax (Python) as presented in Table 8.

Table 8. List of road types and corresponding Volume-Delay Functions.

#	Type	VDF	Aimsun Syntax for VDFs
1	Metered freeway	T0*(2+SQRT(16*(1-(V/C))^2 +1.361)-4*(1-(V/C))-1.167)	(LinkLength(S)/LinkSpeed(S))*(2+SQRT(16*(1-((LinkVolume(S)+LinkAddVolume(S))/LinkCapacity(S)))^2+1.361)-4*(1-((LinkVolume(S) +LinkAddVolume(S))/LinkCapacity(S)))-1.167)
2	Unmetered freeway	T0*(2+SQRT(16*(1-(V/C))^2 +1.361)-4*(1-(V/C))-1.167)	(LinkLength(S)/LinkSpeed(S))*(2+SQRT(16*(1-((LinkVolume(S)+LinkAddVolume(S))/LinkCapacity(S)))^2+1.361)-4*(1-((LinkVolume(S) +LinkAddVolume(S))/LinkCapacity(S)))-1.167)
3	Metered Local Ramp	T0*(2+SQRT(16*(1-(V/C))^2 +1.361)-4*(1-(V/C))-1.167)	(LinkLength(S)/LinkSpeed(S))*(2+SQRT(16*(1-((LinkVolume(S)+LinkAddVolume(S))/LinkCapacity(S)))^2+1.361)-4*(1-((LinkVolume(S) +LinkAddVolume(S))/LinkCapacity(S)))-1.167)
4	Unmetered Local Ramp	T0*(2+SQRT(16*(1-(V/C))^2 +1.361)-4*(1-(V/C))-1.167)	(LinkLength(S)/LinkSpeed(S))*(2+SQRT(16*(1-((LinkVolume(S)+LinkAddVolume(S))/LinkCapacity(S)))^2+1.361)-4*(1-((LinkVolume(S) +LinkAddVolume(S))/LinkCapacity(S)))-1.167)
5	Divided Arterial	T0*(2+SQRT(16*(1-(V/C))^2 +1.361)-4*(1-(V/C))-1.167)	(LinkLength(S)/LinkSpeed(S))*(2+SQRT(16*(1-((LinkVolume(S)+LinkAddVolume(S))/LinkCapacity(S)))^2+1.361)-4*(1-((LinkVolume(S) +LinkAddVolume(S))/LinkCapacity(S)))-1.167)
6	Undivided Arterial	T0*(2+SQRT(25*(1-(V/C))^2 +1.266)-5*(1-(V/C))-1.125)	(LinkLength(S)/LinkSpeed(S))*(2+SQRT(25*(1-((LinkVolume(S)+LinkAddVolume(S))/LinkCapacity(S)))^2+1.266)-5*(1-((LinkVolume(S) +LinkAddVolume(S))/LinkCapacity(S)))-1.125)
7	Collector	T0*(2+SQRT(36*(1-(V/C))^2 +1.210)-6*(1-(V/C))-1.100)	(LinkLength(S)/LinkSpeed(S))*(2+SQRT(36*(1-((LinkVolume(S)+LinkAddVolume(S))/LinkCapacity(S)))^2+1.210)-6*(1-((LinkVolume(S) +LinkAddVolume(S))/LinkCapacity(S)))-1.100)
8	HOV Lane	T0*(2+SQRT(16*(1-(V/C))^2 +1.361)-4*(1-(V/C))-1.167)	(LinkLength(S)/LinkSpeed(S))*(2+SQRT(16*(1-((LinkVolume(S)+LinkAddVolume(S))/LinkCapacity(S)))^2+1.361)-4*(1-((LinkVolume(S) +LinkAddVolume(S))/LinkCapacity(S)))-1.167)
9	Centroid Connector	T0	LinkLength(S)/LinkSpeed(S)
10	HOV Dummy	T0*(2+SQRT(16*(1-(V/C))^2 +1.361)-4*(1-(V/C))-1.167)	(LinkLength(S)/LinkSpeed(S))*(2+SQRT(16*(1-((LinkVolume(S)+LinkAddVolume(S))/LinkCapacity(S)))^2+1.361)-4*(1-((LinkVolume(S) +LinkAddVolume(S))/LinkCapacity(S)))-1.167)
11	C/D Road	T0*(2+SQRT(16*(1-(V/C))^2 +1.361)-4*(1-(V/C))-1.167)	(LinkLength(S)/LinkSpeed(S))*(2+SQRT(16*(1-((LinkVolume(S)+LinkAddVolume(S))/LinkCapacity(S)))^2+1.361)-4*(1-((LinkVolume(S) +LinkAddVolume(S))/LinkCapacity(S)))-1.167)
13	Metered System Ramp	T0*(2+SQRT(16*(1-(V/C))^2 +1.361)-4*(1-(V/C))-1.167)	(LinkLength(S)/LinkSpeed(S))*(2+SQRT(16*(1-((LinkVolume(S)+LinkAddVolume(S))/LinkCapacity(S)))^2+1.361)-4*(1-((LinkVolume(S) +LinkAddVolume(S))/LinkCapacity(S)))-1.167)
14	Unmetered System Ramp	T0*(2+SQRT(16*(1-(V/C))^2 +1.361)-4*(1-(V/C))-1.167)	(LinkLength(S)/LinkSpeed(S))*(2+SQRT(16*(1-((LinkVolume(S)+LinkAddVolume(S))/LinkCapacity(S)))^2+1.361)-4*(1-((LinkVolume(S) +LinkAddVolume(S))/LinkCapacity(S)))-1.167)
15	Expressway	T0*(2+SQRT(16*(1-(V/C))^2 +1.361)-4*(1-(V/C))-1.167)	(LinkLength(S)/LinkSpeed(S))*(2+SQRT(16*(1-((LinkVolume(S)+LinkAddVolume(S))/LinkCapacity(S)))^2+1.361)-4*(1-((LinkVolume(S) +LinkAddVolume(S))/LinkCapacity(S)))-1.167)
18	HOV Bypass	T0*(2+SQRT(16*(1-(V/C))^2 +1.361)-4*(1-(V/C))-1.167)	(LinkLength(S)/LinkSpeed(S))*(2+SQRT(16*(1-((LinkVolume(S)+LinkAddVolume(S))/LinkCapacity(S)))^2+1.361)-4*(1-((LinkVolume(S) +LinkAddVolume(S))/LinkCapacity(S)))-1.167)

After translating the VDFs into Aimsun, additional corrections were made on both normal links and centroid connectors. In both cases, delays calculated by Aimsun were in the wrong unit which caused truncation errors resulting in unreasonable route selection. Modifying the VDFs with a simple correction coefficient eliminated this error.

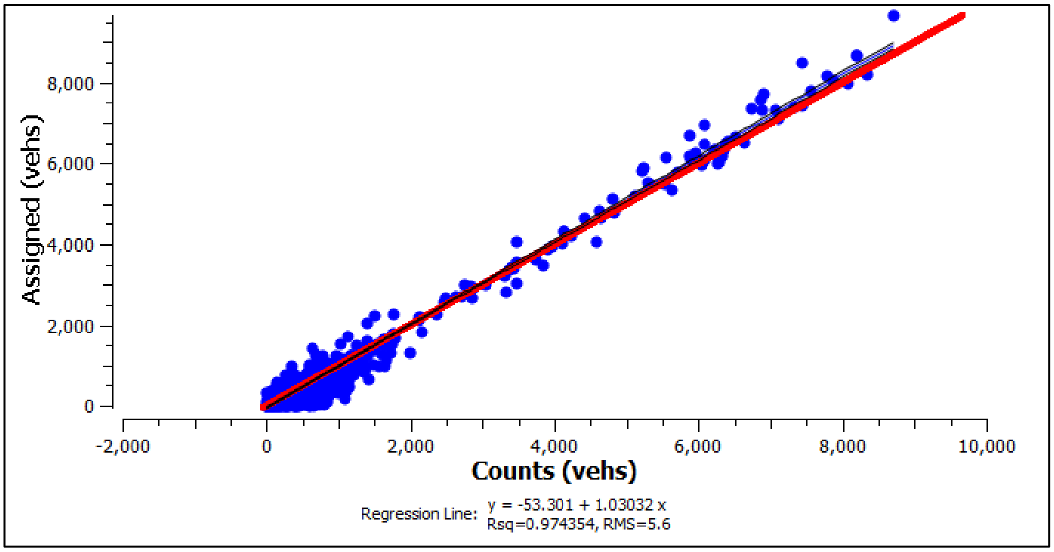
In relation to HOV lanes along I-35W, one final adjustment was made to some VDFs. Within the RPM the MnPASS HOT lanes are modeled as separate links which connect with the rest of the road network at various points to allow vehicles in and out of the HOT lane. Those entry points are controlled to allow only HOV/truck type vehicles onto the HOT lane. Aimsun does not include a straightforward method to replicate this behavior. Instead, the VDFs for those specific links were adjusted to significantly penalize single occupancy vehicles.

Collectively the changes made to correct centroid-related issues and those dealing with VDFs are referred to as Steps 2 through 4.

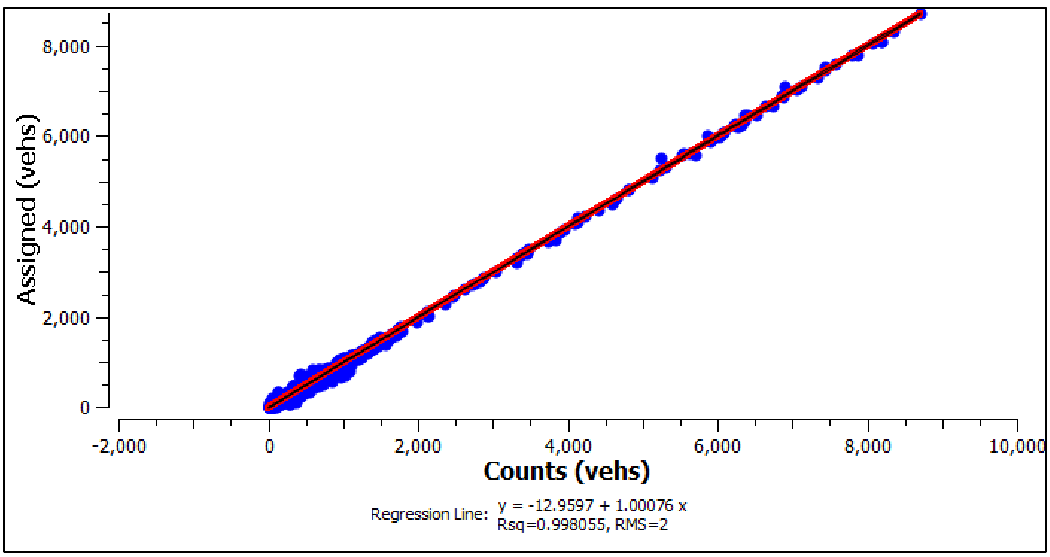
4.1.4 RESULTS OF MACROSCOPIC VALIDATION

As was indicated above, the validation focused on comparing link volumes between the Aimsun macroscopic STA and the results from the Voyager RPM. Figure 15-A and Figure 15-B which are produced after steps 1 and 4 respectively for university sub-network. Table 9 makes this comparison possible using the amount of two models discrepancy for both sub-networks.

The remaining dissimilarity is acceptable because it probably comes from being under capacity (close to free flow condition) in a large number of sections. Being considerably under capacity causes that sections' travel time not to be sensitive to moderately small changes in their volume.



A) After step 1



B) After step 4

Figure 15. Predicted vs observed values plot for the macro model (University sub-network 7:30-8:30).

Table 9. Relative difference between two models (7:30-8:30).

	Maximum Relative Difference (percent)			
	Green Line		**Blue Line**	
Percent of Sections	**After step 1**	**After step 4**	**After step 1**	**After step 4**
75%	63	14.3	75	19.6
50%	31	6.5	39	8.3
25%	10	2.1	15	3.1

4.2 Calibration Approaches

After moving beyond the macroscopic level, various methods were used to calibrate the microscopic subarea models surrounding both Green and Blue LRTs, as well as the broader integrated hybrid model. Within the smaller networks, manual calibrations were primarily used. Manual calibration involved running simulations and examining network behavior both as the simulation evolved and following run completion to identify irregularities in behavior. Unusual speed and density patterns, lost vehicles, and other factors characteristic of poor calibration were used to isolate localized areas requiring additional refinement.

Once the subarea networks were integrated into the larger regional hybrid model, manual calibration techniques became unusable due to the immense breadth of the network and the significant time cost to perform each iteration of simulation. Whereas a loop between making a change and observing altered behavior would take on the order of 15-45 minutes within the smaller networks, the full network model required multiple hours. As such, alternative calibration strategies were used. These 'blanket calibration' techniques involved adjusting parameters for larger blocks of the network simultaneously, either by region or by targeting a particular subset of the network (e.g., all roads of a certain type, all nodes, etc.).

4.3 Manual Calibration

In order for the models to mimic actual traffic conditions on Twin Cities roads, calibration and validation of the models were necessary. To do this, parameters and geometry were assessed and adjusted within the model so that driver behavior was realistically captured on roads of interest. Validation was generally performed by cross-checking the traffic conditions output by the model with real traffic data provided by local agencies.

4.3.1 CALIBRATION VIA DYNAMIC SCENARIO EXPERIMENTS

In order to calibrate parameters in the Aimsun microscopic network, Aimsun used what are called dynamic scenario experiments. The different scenarios consist of two different Graphical User Interface (GUI) menus for selecting inputs. The first menu, the Dynamic Scenario, contained the collected information on how to run each scenario in a broad aspect. This can be seen in Figure 16 where information such as which Traffic Demand, Public Transit Plan, Master Control Plan, Outputs, etc. are defined.

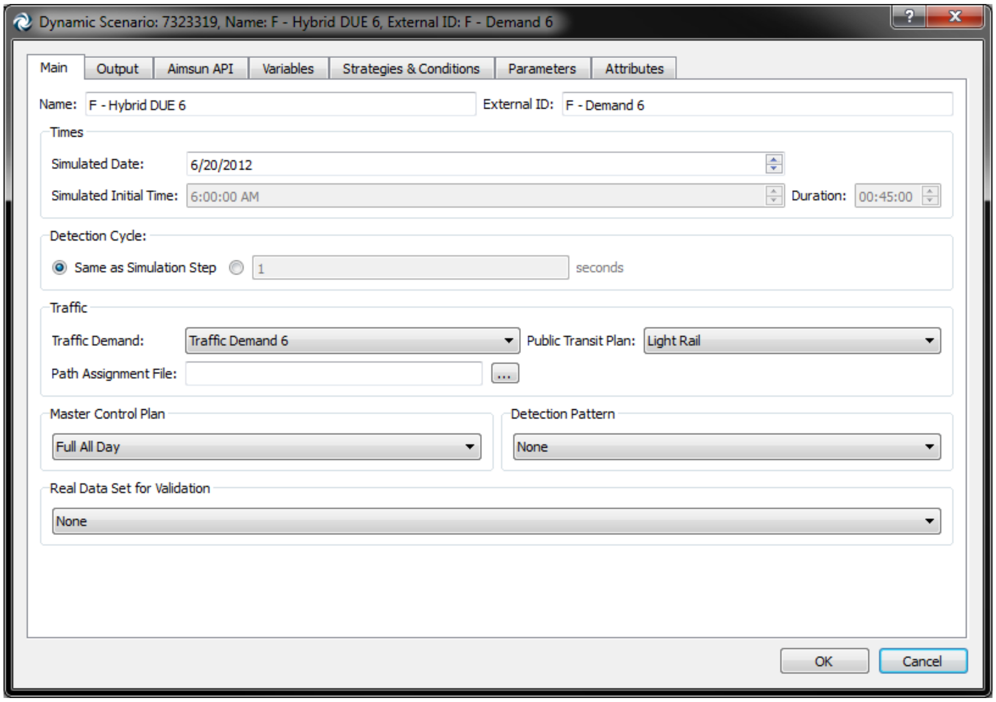


Figure 16. Graphical user interface for a Dynamic Scenario in Aimsun.

The second menu, the Dynamic Experiment seen in Figure 17, contained the more refined inputs such as the parameters of the stopping criteria, micro simulation subareas, global behavior and reaction time parameters, arrival pattern, Dynamic Traffic Assignment parameters, and active Policies (forced turnings, time sensitive lane/movement closures, etc.)

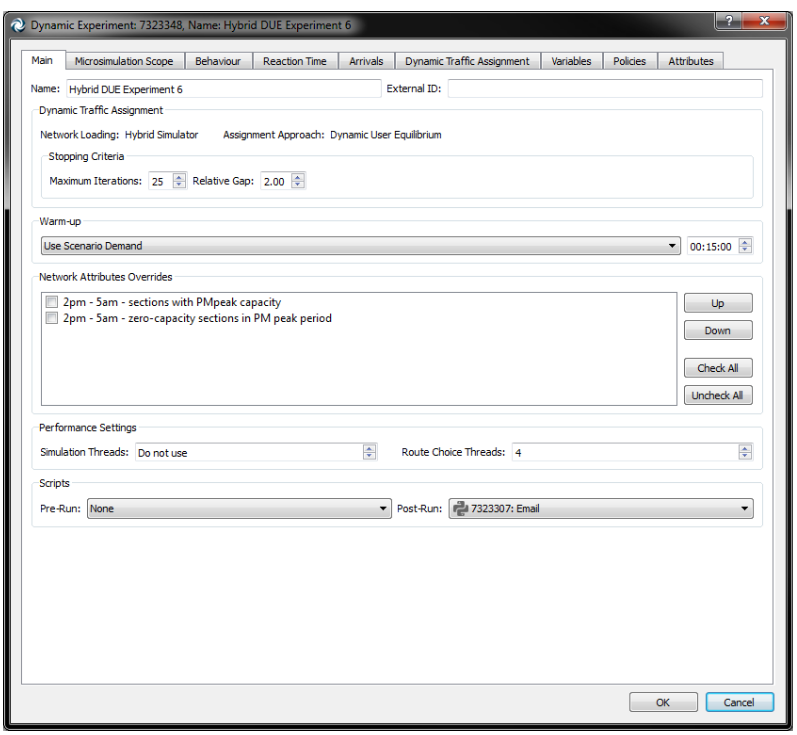


Figure 17. Graphical user interface for a Dynamic Experiment in Aimsun.

The model was also run using multiple view modes in order to identify specific areas which did not capture realistic conditions. This was accomplished by using Aimsun's built in view options. Some of the useful view modes for calibration that were used include:

- Lost Vehicles
  - Highlight lost vehicles with large star to easily identify while zoomed out and locate problem areas.
- Density/Jam Density
  - Highlight and label sections that are close to their theoretical limit of density.
  - Used to determine if links were realistically congested or near jam density due to simulation gridlock.
- Speed/Speed Limit
  - Highlight sections that have an average speed well below their speed limit.
- Color By Turn
  - Color a vehicle based on how it will turn in the next node to help determine if distance zones were correct and that vehicles were moving to the appropriate lanes early enough to make their intended turn.
- Missed Turns by Node
  - Color nodes based off the number of missed turns that have occurred inside them to identify nodes that had geometric or other issues that did not allow turns to be completed properly.

This calibration effort was conducted separately for the Blue Line and Green Line Corridor models prior to joining the two high-resolution networks together. This approach was taken so that each model run could be completed in a reasonable amount of time thus allowing a trial and error method to be feasible. Common problems which were addressed include instances of lost vehicles and missed turns, improperly functioning traffic signals, inappropriate lane changing distance zones, and inappropriate route selection requiring forced turnings.

These techniques were also applied to the final Hybrid model but were found at the time to be infeasible due to the size of the model. Therefore more extensive calibration was done within the smaller region models before moving into the hybrid model. Once in the hybrid model, only broad calibrations were made. The calibration efforts described in the remainder of this section were mainly from where the two smaller networks were joined. Recent advances have made the process of running graphical large scale hybrid simulations feasible but still too time intensive to calibrate at that scale in a reasonable amount of time.

4.3.2 MISSED TURNS AND LOST VEHICLES

Missed turns and lost vehicles are related in the fact that you can only have a lost vehicle if it had missed at least one turn but could have vehicles that miss turns but are not considered "lost." Lost vehicles are vehicles that have missed a turn and due to network geometry programed in the network can no longer make it to their intended destination. When calibrating the small sub networks this came up frequently towards the fringes of the network as almost all other locations had enough roads so that if a vehicle missed a turn it could find a new path to its destination.

To identify problem areas causing missed turns and lost vehicles, manual view modes were created. A frequently used one involves simulation vehicles that have missed at least one turn to be indicated with a preset symbol of a specific pixel size so that they could be identified at any altitude level. In conjunction with the aforementioned manual view mode, nodes were colored to denote how many turns were missed within them. Addressing missed turns reduces the occurrences of lost vehicles as well.

Instances of lost vehicles and missed turns were found to have three primary causes: some were legitimate missed turns due to traffic congestion not allowing the required lane change, some were due to inadequate road parameters within the model, and others were caused by a bug in Aimsun version 7.0.2 that was later fixed in version 7.0.3. The missed turns and lost vehicles caused by inadequate road parameters were addressed by determining the problem and subsequently changing the responsible parameters. Frequently occurring problems included inadequately sized turn pockets, improper distance zones pertaining to lane changing, and road splits requiring forced turnings.

The network geometry originally included the short turn pockets that are frequently present in residential areas or with heavily utilized on-street parking. While this was initially thought to be a good idea, due to a limitation of Aimsun, vehicles are unable to conduct their turn without fully merging into the turn pocket, which makes it impossible for larger vehicles such as trucks and buses to conduct these turns. As a result they end up driving around consistently missing turns and are unable to get to their destination. To resolve the issue, the majority of turn pockets were removed entirely, and some extended when appropriate to allow for larger vehicles to use them.

4.3.3 DISTANCE ZONES

Roads with higher speed limits, specifically highways, were more likely to be subject to inaccurate look-ahead distance zones for lane changing. The default value in Aimsun alerted individual vehicles to make their lane changes while at free flow speed too late, sometimes with only 100 feet before an exit. This caused missed turns and in cases where vehicles stopped to attempt to make their turn, impeding traffic. This was addressed by manually adjusting the look-ahead distance zones for areas that demonstrated this problem to a feasible value while also globally increasing the zones on all freeways to be more accurate to real world conditions.

4.3.4 FORCED TURNINGS

During the initial debugging and calibration, it was observed that in several specific areas assigned routes for vehicles utilizing highways would often reflect "incorrect" choices as intended by the road's design. An example of such an event was found near downtown St. Paul that caused missed turns and subsequently some lost vehicles and unnecessary congestion. It dealt with the dedicated off ramp from southbound Interstate 35E to southbound U.S. Highway 52 (Figure 18). Aimsun calculates its cost based on distance and travel time and in some cases concluded that merging onto I-94 and then off on US 52 would be preferred. This maneuver requires three lane changes on I-94 in 140 m which infeasible under almost any traffic conditions.

This was the preferred route choice despite that the ramp had no vehicles utilizing it as seen in Figure 19. On the upper left, vehicles heading toward both I-94 and Highway 52 share a ramp (blue shaded region). A dedicated slip ramp connects I-35E and Highway 52 and is the correct route for vehicles to take (green shaded region). Aimsun incorrectly directed vehicles toward I-94, across several lanes of traffic, and onto the I-94/Highway 52 ramp (red shaded region).

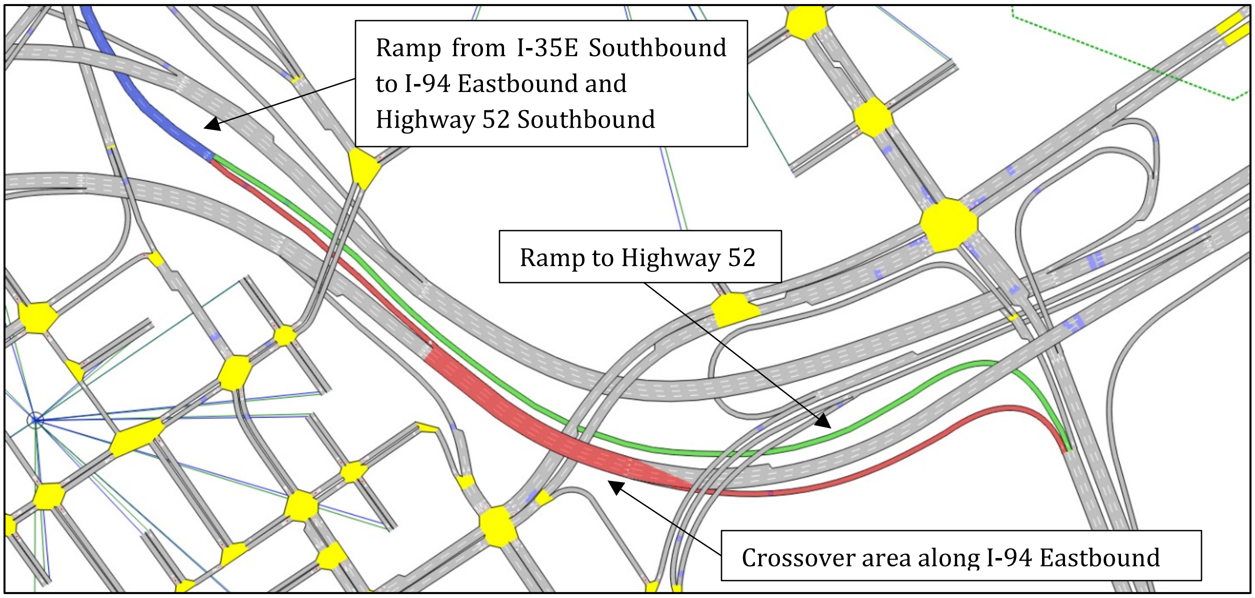


Figure 18. Problematic connections between I-94, I-35E, and Highway 52.

To remedy this incorrect route selection pattern, a forced turning was created which guides any vehicles entering the shared ramp space onto the correct slip ramp if their destination links include Highway 52. This forced turning mirrors the real-world lane indications (shown in Figure 19) which direct traffic to the appropriate routes. Figure 20 shows the Force Turning dialogue for this case.

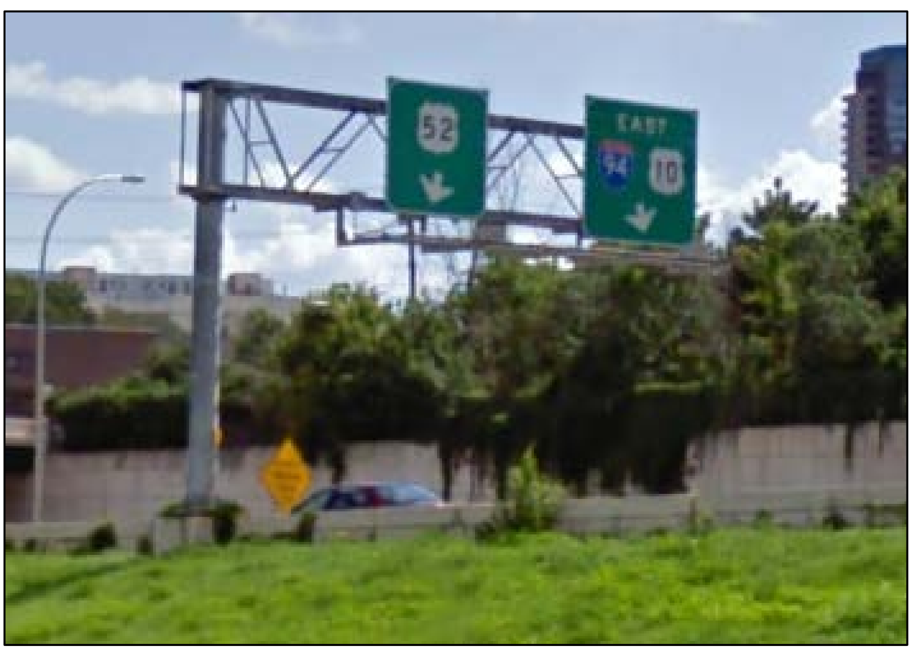


Figure 19. Real world signs guiding drivers in route selection.

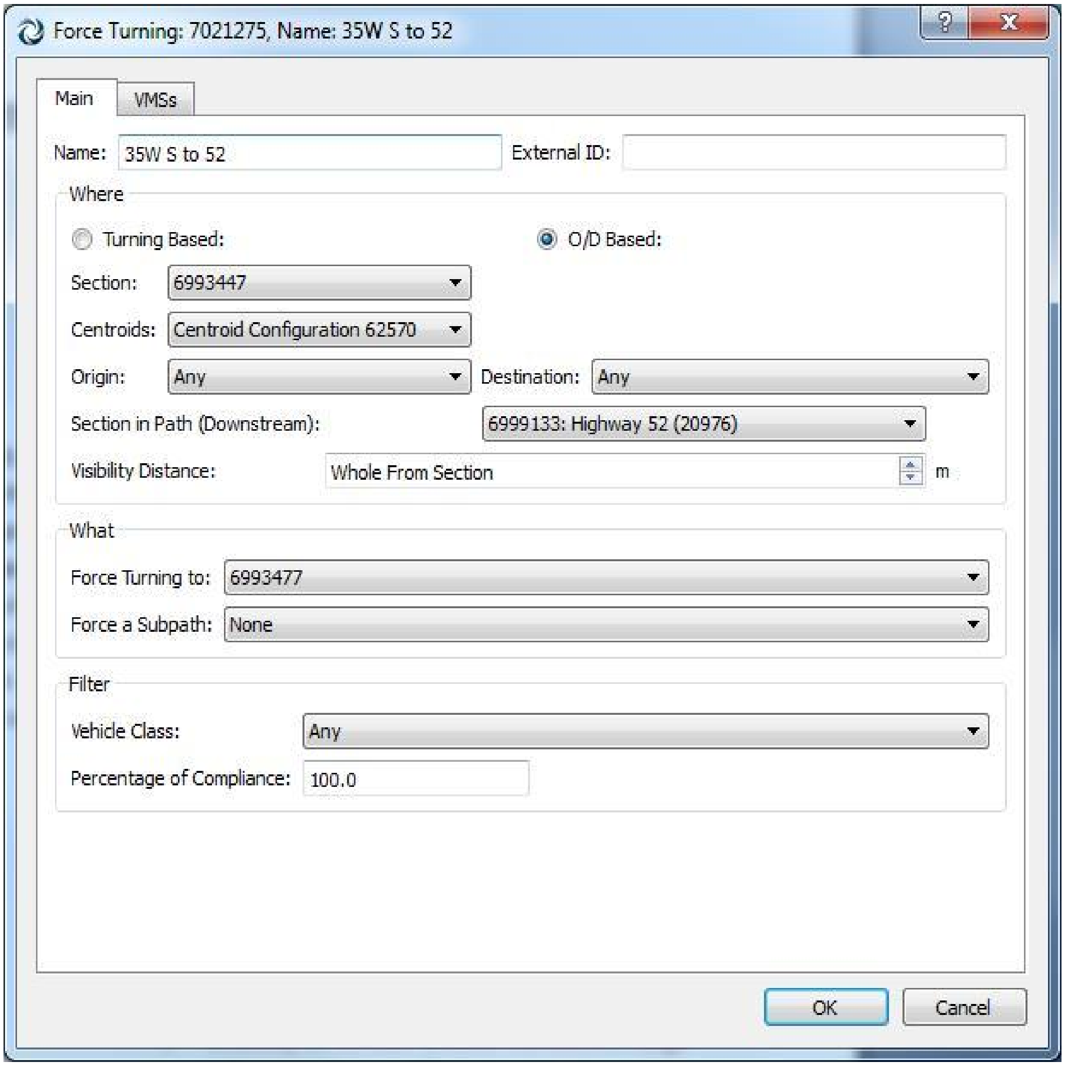


Figure 20. Forced turning dialog menu in Aimsun.

Additional routes demonstrated similar issues, including the interaction of I-35E and I-94. There are two forks in the road that distribute traffic to the correct side of the merge point to reduce the amount of lane changes. Unfortunately, as described before, Aimsun chooses the wrong lane and this causes unnecessary lane changes that create congestion. The four instances found and addressed are:

- Northbound I-35E to northbound I-35E
- Northbound I-35E to eastbound I-94
- Southbound I-35E to southbound I-35E
- Southbound I-35E to westbound I-94

4.3.5 LINK VOLUMES AND LINK TRAVEL TIMES

View modes were created that displayed link volumes and link travel times. These highlighted areas of congestion that were unrealistic and requiring fixes. In some instances, traffic signals were not properly functioning, due in some cases to human error while programming the signal, instances of broken or missing links, or because force-offs required recalculating. In others, due to programming limitations in Aimsun 7.0.4 and below, vehicles were not allowed to merge at different points in the queue, creating a chain reaction of vehicles stuck on or queued for the on-ramp. This was solved by using the lane change cooperation parameter. Each problem section had to be looked at individually, and with the combination of data provided by MnDOT's detector data, was calibrated to fit realistic results. Aimsun 8.0.4, released in the spring 2014, now has the ability to allow cars to merge at different points in the queue. This will be discussed further in the bugs section.

4.3.6 MODEL VALIDATION

To validate the microscopic and mesoscopic models, real data collected in the field were necessary. Turning vehicle counts were provided by the cities of Minneapolis and St. Paul in various formats and from varying time periods. Ultimately, for intersections within the city of Minneapolis, the data provided was contained within a proprietary software format, PETRAPro. The city of St. Paul provided turning vehicle count data in PDF for some intersections and Excel for others. The data in spreadsheet format was used, whereas the data in PDF was only used sparingly for crucial intersections due to the significant manual effort required to convert the data into a useable form.

Each intersection with data from the city of Minneapolis was contained within an individual PETRAPro file. To extract and convert this data into a spreadsheet format comparable to the St. Paul data, an open source scripting program was created that repeated an embedded function in PETRAPro to convert the files accordingly. Once all desired intersections from both cities were compiled, a script was written to merge all individual spreadsheets into a single file.

In order to apply the real data to the microscopic network, the data was manually sorted and mapped, after which each turning movement with data was matched with its corresponding ID in the Aimsun network. Manually traversing through the consolidated spreadsheet, each intersection's geographic location was pinned in Google Maps, as demonstrated in Figure 21 and Figure 22, or if the intersection was not located within the confines of the microscopic network, its data was removed from the spreadsheet. After all intersections were pinned, the map was scrutinized and supplementary data for missing significant intersections were obtained from different sources, including older turning count data available online through the city of Minneapolis.

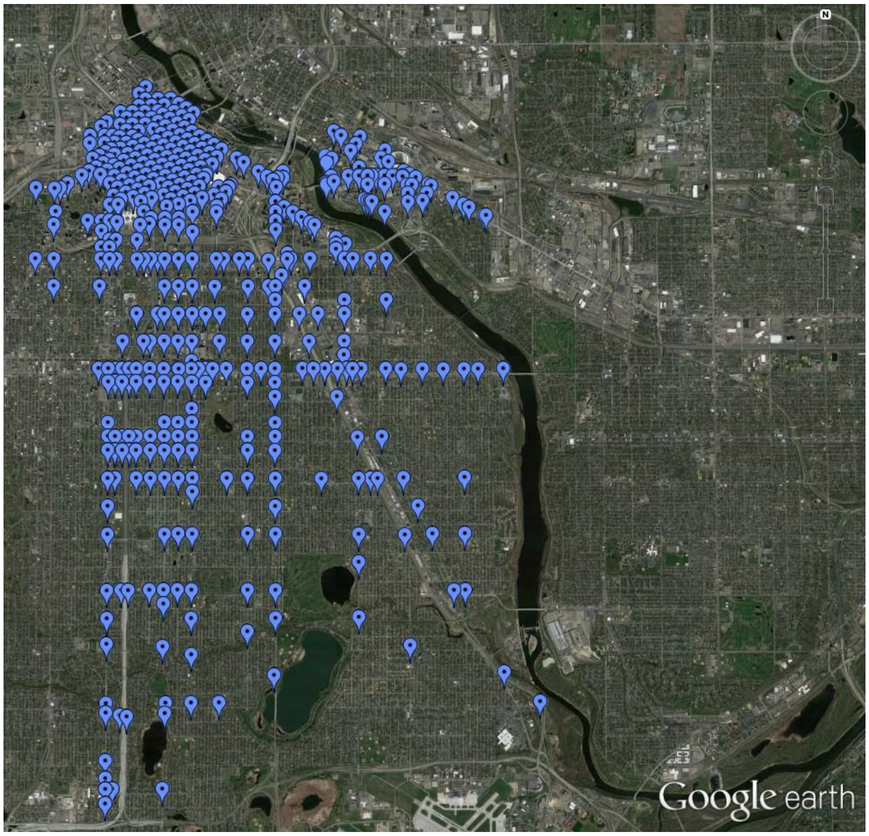


Figure 21. Locations of Minneapolis turning count data.

Figure 22. Locations of St. Paul turning count data.

With the data prepared for each intersection, each turning movement was matched with its corresponding turning ID in Aimsun. This involved manually locating each intersection containing data and copying the turning ID for each existing turning movement to the corresponding turning count in the spreadsheet, as demonstrated in Figure 23 and Figure 24. For turning movements that did not exist (i.e., in the case of a one-way road), the output file contained all zeroes, therefore an ID of -100 was given to indicate that it was an invalid turning movement and would be excluded from the final consolidated data.

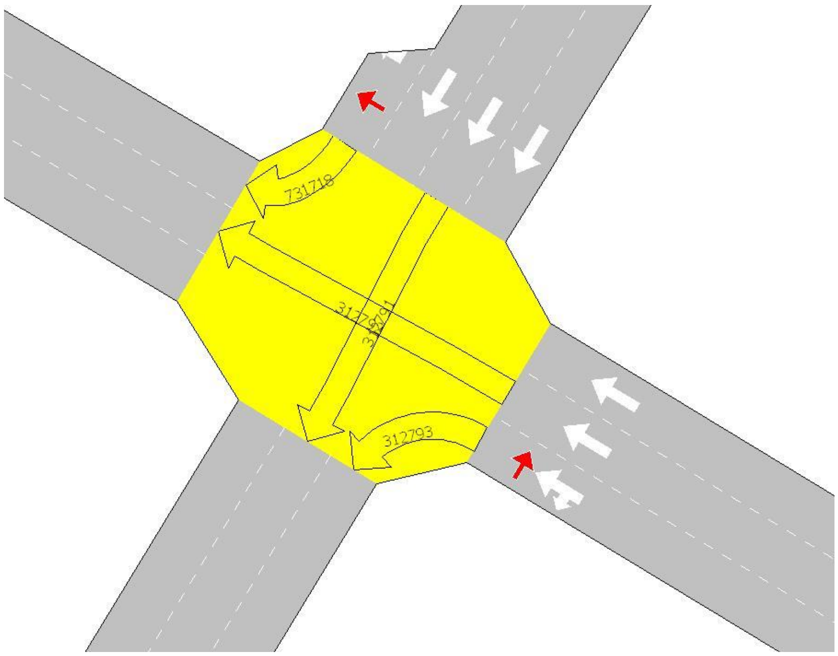


Figure 23. Accessing intersection turning IDs in Aimsun.

5/19/2011	Portland Ave S From North			3rd St S From East			Portland Ave S From South			3rd St S From West		
	731718	312791	-100	-100	312792	312793	-100	-100	-100	-100	-100	-100
Start Time	Right	Thru	Left	Right	Thru	Left	Right	Thru	Left	Right	Thru	Left
7:00 AM	10	54	0	0	71	13	0	0	0	0	0	0
7:15 AM	6	92	0	0	80	31	0	0	0	0	0	0
7:30 AM	13	80	0	0	97	28	0	0	0	0	0	0
7:45 AM	21	123	0	0	118	19	0	0	0	0	0	0
8:00 AM	18	95	0	0	116	27	0	0	0	0	0	0
8:15 AM	17	91	0	0	125	21	0	0	0	0	0	0
8:30 AM	21	84	0	0	114	22	0	0	0	0	0	0

Figure 24. Sample of spreadsheet for matching real data to turning IDs.

Another macro in Visual Basic was written to consolidate the data into a format that Aimsun is able to read and subsequently use as real data. The consolidated data included three columns: Aimsun turning ID, time of day, and real data turn count. This formatted data was used in addition to the freeway detector data to fine-tune the microscopic and meso-fine portions of the hybrid model to best represent the standard conditions in these areas.

The results of the available turning counts ended up being inconsistent with each other. Due to the vast degree of the scope and quality of the turning counts, they were less useful than the freeway detectors. The turning counts were found to vary greatly over both the years taken along with the time of year. Therefore they were used mostly to find intersections that had very contrasting counts to see if there were issues with the particular nodes that those counts belong too.

It was found that the overall convergence of the model got closer to freeway detector counts as the model approached the peak periods. Figure 25, Figure 26, and Figure 27 below show that as the model approaches Demand 8 (7:30-8:30) the model is getting closer to convergence and a "give/take" balance between having too many vehicles and not having enough. When the model had fewer vehicles it was found that they used more arterials then the highway detectors would suggest.

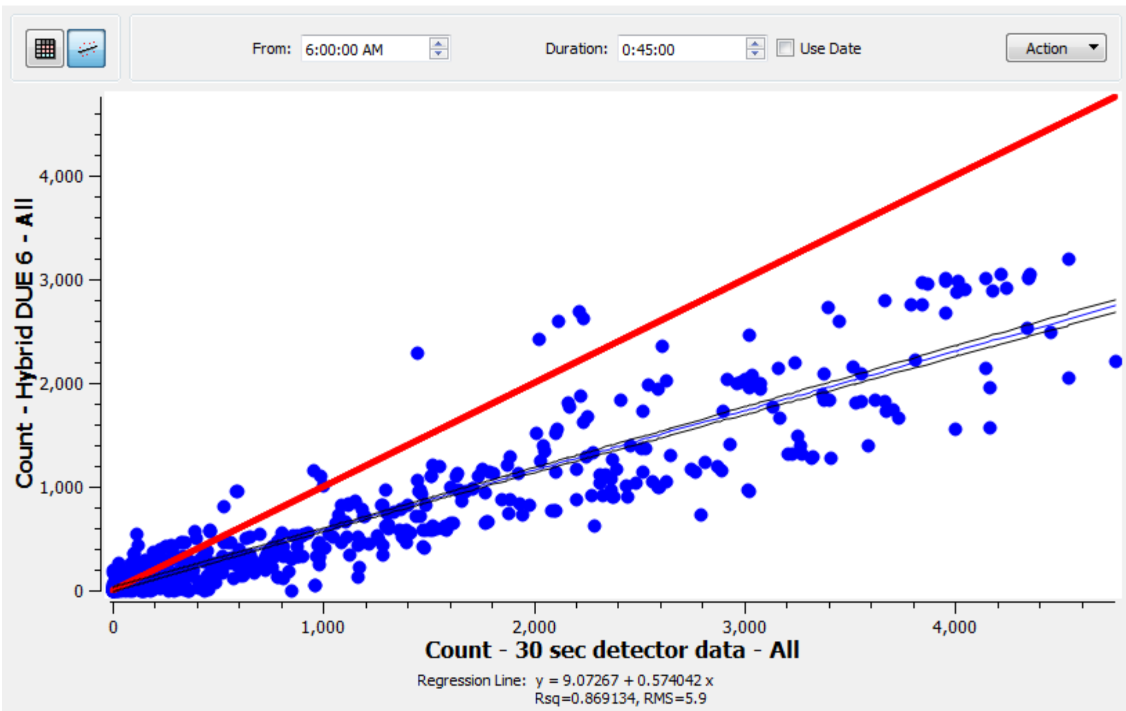


Figure 25. Demand 6 highway detector convergence.

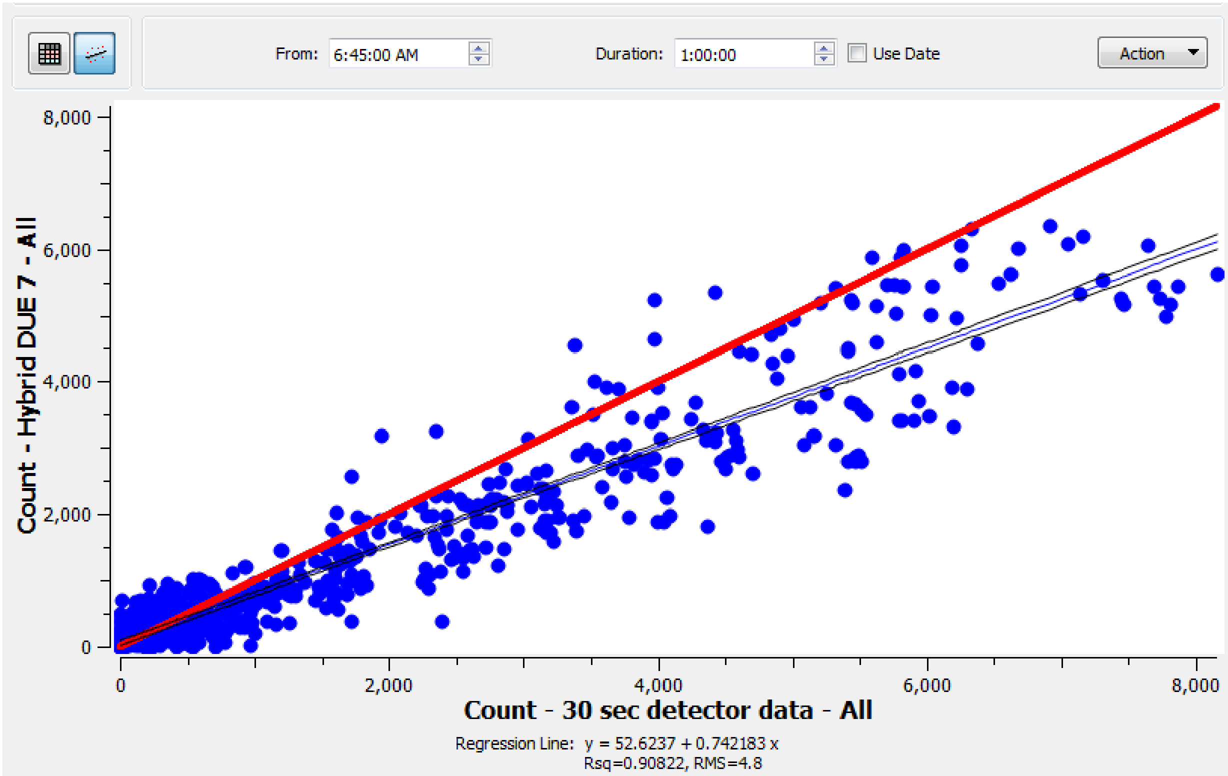


Figure 26. Demand 7 highway detector convergence.

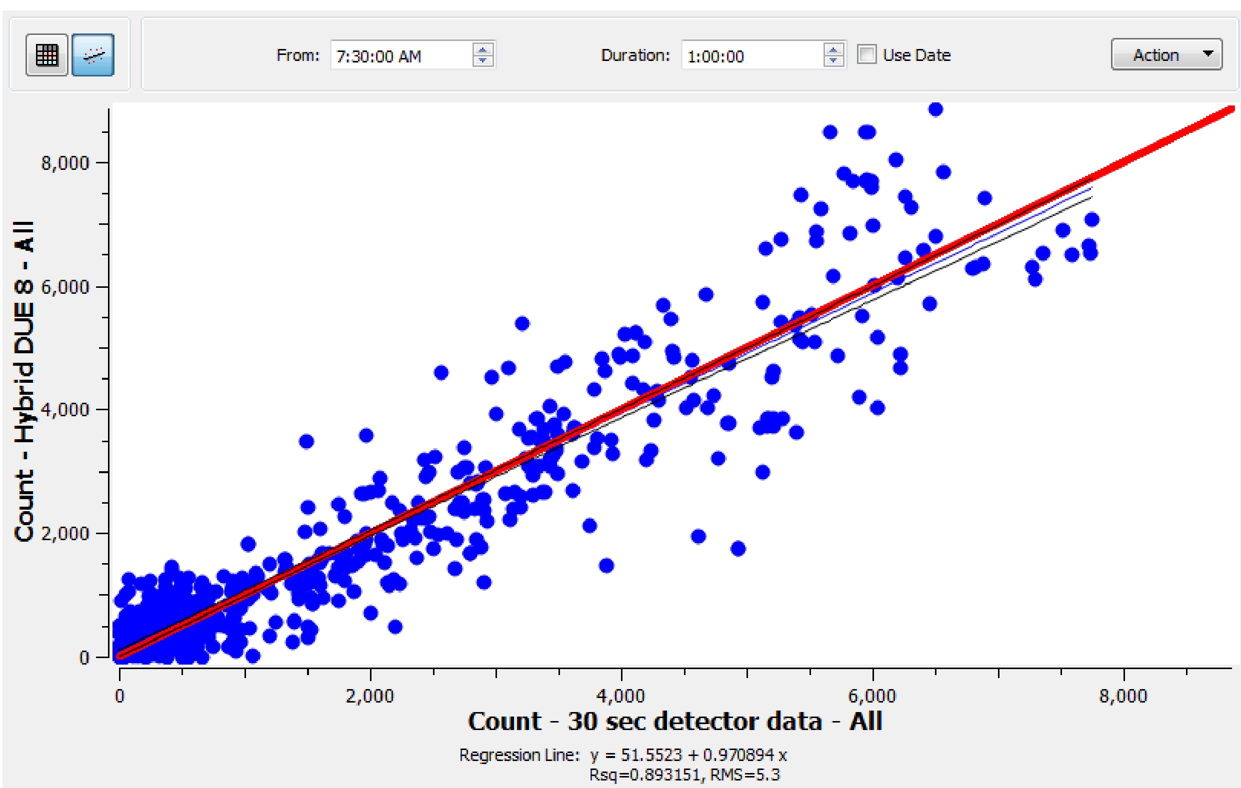


Figure 27. Demand 8 highway detector convergence.

4.4 Mesoscopic Calibration

Within the mesoscopic regions of the network, three major parameters govern traffic movements within each link: free flow speed, jam density, and reaction time. From these parameters, a triangular fundamental diagram (Figure 28) is developed for each link to govern the relationship between speed and volume. Free flow speed was inherited from the RPM and, as such, was treated as pre-calibrated. This left two parameters with which to adjust behavior in the mesoscopic regions of the network. Related to these parameters, link capacities were also inherited from the RPM. Thus, an approach was developed to fix jam density based on road type and adjust reaction time on a link-by-link basis to target the capacities given by the RPM to produce calibrated fundamental diagrams across the mesoscopic region.

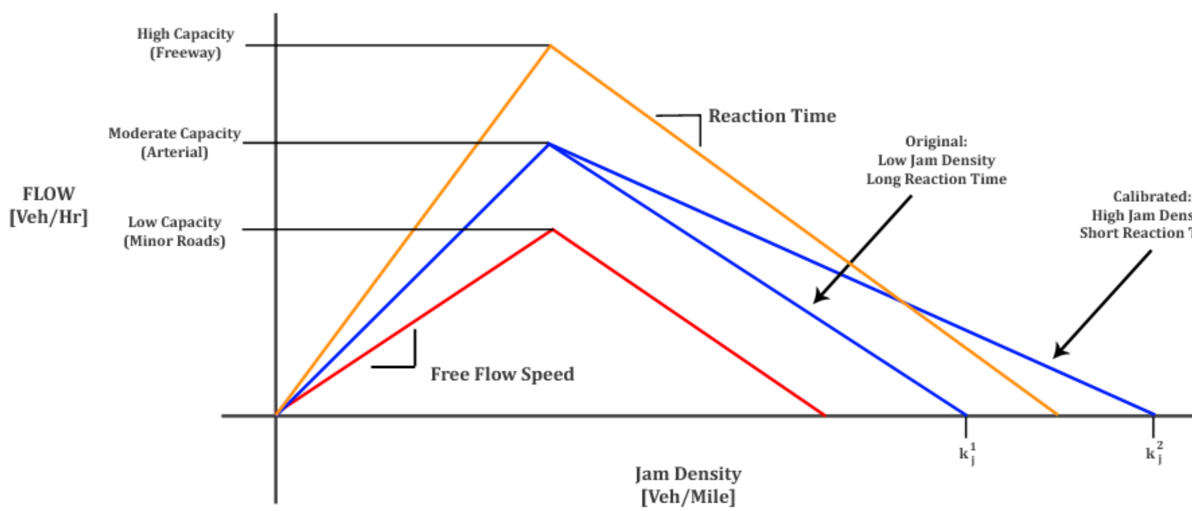


Figure 28. Mesoscopic triangular fundamental diagram.

This process was confounded by the way in which nodes treat vehicles in Aimsun's mesoscopic simulator. Each node acts as an event server, processing a queue of vehicles over the lifetime of the simulation. For every vehicle passing through the node, an arrival time is assigned based on the departure from the upstream node and link travel time. When control exists within the model, a delay function is used to assign a travel time for each vehicle using the node. Those vehicles then determine their travel time for the next link, are assigned a node arrival time for the next node, and are removed from the current node.

However, when no control exists, such as the entirety of the meso-rough portion of the hybrid model, Aimsun falls back on a first-in-first-out rule where vehicles entering the node are served in order (with parallel, non-overlapping movements allowed to occupy the node simultaneously). Between vehicles on conflicting turnings, a safe headway allowance is specified which is dependent on reaction time. As reaction time grows, these headways increase dramatically, limiting the total throughput of each node. This acts as an upper barrier on calibrating reaction time as well as capacity. In certain locations, this limitation created additional congestion in the broader meso-rough region.

Aimsun in certain circumstances loaded enough traffic onto links to exceed jam density. Vehicles entering the link after such an instance were assigned speeds of zero or negative values. Such links broke down severely causing stand-still conditions upstream in a link-by-link cascade. Adjusting individual jam densities to avoid this problem served to alleviate the problem in one location but simply push it further downstream. As the hybrid model targeted the light rail corridors, these problems were traced through the network until their cascade effects did not impact the microscopic areas, minimizing their total influence on the final results.

4.5 Bugs

During Calibration many bugs were found where the network would break down due to the simulator working incorrectly and not as a result of the parameters. These issues were brought to the attention of TSS and they worked closely to resolve many of our issues with custom builds. It was found however that the size of our model has a significant impact on the amount of issues that arise since in many cases we were unable to reproduce the errors in smaller "toy" networks. This compounded the issue since the simulations took full days to run and special hardware. However many of the issues were able to be resolved.

4.5.1 AIMSUN DENSITY BUG

One particular issue that was encountered while calibrating the model was a bug present within the Aimsun Mesoscopic simulator. In some instances, links will become highly saturated with vehicles and the density will approach jam density. While this is reasonable and does occur in certain locations within the network at peak times, vehicles maintain positive speed and proceed, albeit slowly, through the link.

In certain circumstances, the Aimsun simulation will assign speeds of zero or minus one to vehicles in links that reach densities above jam density. This causes the link to stop passing vehicles downstream. Eventually, the capacity of the link is completely consumed and the next upstream links begin to completely halt as well, forming a cascade further and further upstream.

Although we have been working with the software developers to solve this problem, only minimization of the problem has been achieved and still we do not have a completely bug free application available. The bug is elusive in the sense that we have failed to replicate it in a smaller network therefore we hypothesize that the very large size of the Twin Cities model somehow contributes to the problem. In order to minimize the impact of this problem, jam densities were increased incrementally and geometries were improved to more accurately represent real-world turnings and conflicts while simultaneously decreasing the likelihood of causing severe breakdowns.

By addressing this problem in one location, heavily trafficked areas became 'unclogged' and allowed much larger flows to proceed downstream. Often some subsequent bottleneck point would then trigger the bug and cause a new cascade which would require its own treatment. While this methodology could eventually eliminate the problem, the scope and time constraints of this project only allowed sufficient effort to push such incidents far enough away from the core region of interest so that the cascade effects did not reach the boundaries of the microscopic region. Ideally, a more carefully calibrated mesoscopic surrounding region could be implemented, but significant effort would be required to manually examine and improve geometries and turnings, as well as potentially hundreds of test runs to diagnose incidents of the bug and implement a correction.

4.5.2 ON-OFF RAMPS

During the course of calibration it was found that a particular issue was causing issues on freeways. In version of Aimsun prior to 8.0.4 (which was not released until the spring of 2014 near the end of the project) cars were not able to merge from the on ramp unless all the vehicles in front of them had merged. In other words every ramp was operating under first in first out. This was mainly an issue when particular large onramps that essentially add an auxiliary lane for a section of freeway would not allow any (except the lead vehicle) to merge on the freeway. If this vehicle could not find a gap then it would come to a stop at the end of the ramp and vehicles would cue up behind them as seen in Figure 29.

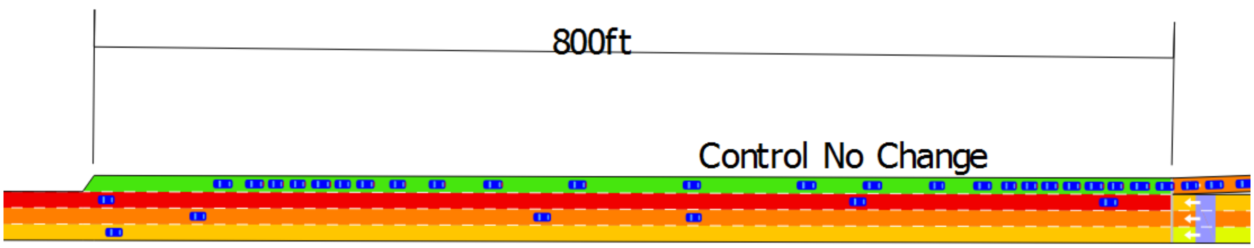


Figure 29. On ramp queue formation.

In an attempt to solve this issue a small network was made and many different variables were used in an attempt to get realistic results. To mitigate the issue parameters such as the length of the ramp were artificially extended to provide more time to find gaps. In the end it was found that a combination of the “Lane Change Cooperation” parameter and the use of the two-lane car following model (which reduces the speed of vehicles in adjunct lanes) produced the best results. This still however did not solve the issue where only the lead vehicle could merge. The feature to allow different vehicles in the queue to merge first was added to Aimsun 8.0.4 but this was toward the end of the project and not used to its fullest extent.

5. Results

The introduction of the Green Line caused changes to traffic patterns across the region between the Minneapolis and Saint Paul downtown areas. To quantify these changes, whole-period flow, travel time, speed, and densities were compared.

5.1 Aimsun Output

Aimsun has a range of outputs that can be selected and exported at the end of the simulation. For the purpose of our analysis the outputs needed were those of the sections. While more could have been selected, they would require more memory and time to be computed. The computational requirements of the model were extensive and every effort was made to reduce these needs, which are discussed later in Chapter 6. Therefore the available output statistics from Aimsun can be seen in Table 10 below. These were output at the end of each simulation run at 5 minute intervals.

Table 10: Aimsun Hybrid Section Database Outputs

Name	Type	Description
did	integer	Replication or Average identifier
oid	integer	Section identifier
eid	char	Section External ID
sid	integer	Vehicle type (from 0 for all vehicles, to number of vehicles)
ent	integer	Time interval, from 1 to N, where N is the number of time intervals, and 0 with the aggregation of all the intervals
flow	double	Mean flow (veh/h)
count	Integer	Vehicle counts (veh)
ttime	double	Mean Travel Time (seconds)
dtime	double	Mean Delay Time (seconds)
speed	double	Mean speed (km/h)
spdh	double	Harmonic mean speed (km/h)
flow_capacity	Double	Mean flow / section capacity
density	double	Density (veh/km)
qmean	double	Mean queue length by lane (veh)
qmax	double	Maximum queue length (veh)
qvmean	double	Mean virtual queue (veh)
qvmax	double	Maximum virtual queue (veh)
travel	double	Total number of km travelled in the section travel time double Total travel time experienced in the section (seconds)
lane_changes	double	Number of lane changes / Number of veh
stime	double	Mean Stop Time (seconds)
fuelc	double	Total liters of fuel consumed in the section
nstops	double	Number of stops per vehicle

5.2 Visualizing Results

In order to visualize the results the database outputs were cleaned and associated into useful measurements. Since ArcMap was used to visualize the data, and given the large quantity of data produced by each simulation, the data needed to be in a format that was easy to import into ArcMap and one which did not have to query the database. Access was chosen to do all the calculations and to format the data.

The first step was to choose which network was going to serve as a base map for ArcMap. Since the two networks only varied in geometry around the Green Line Corridor, it was chosen to use the network that reflected the geometry of the road after the Green Line implementation. Since the network was edited to insert the Green line, Aimsun renumbered several sections causing some issues in associating links between the two geometries. To resolve this, the network was visually compared and a link map associating the before and after changes along the green line corridor was made to allow the two networks to be compared.

With a base map and both networks associated to their corresponding sections, the task of computing the useful outputs proceeded. The four main outputs were compared both as absolute differences and as percent change shown in Table 11. The Access structure for associating the different data sets is shown in Figure 30.

Table 11. Performance measurements extracted from database outputs

Measurement Type	**Statistic**	**Query**
Absolute Difference (After – Before)	Speed	AbsD_Speed: ([After_678.speed]-[Before_678.speed])
	Flow	AbsD_Flow: [After_678.flow]-[Before_678.flow]
	Density	AbsD_Density: ([After_678.density]-[Before_678.density])
	Travel Time	AbsD_ttime: ([After_678.ttime]-[Before_678.ttime])
Percent Change ((After – Before) /Before * 100)	Speed	PerD_Speed: (([After_678.speed]-[Before_678.speed])/[Before_678.speed])*100
	Flow	PerD_Flow: IIf([Before_678.flow]=0,[After_678.flow]*100,(([After_678.flow]-[Before_678.flow])/[Before_678.flow])*100)
	Density	PerD_Density: (([After_678.density]-[Before_678.density])/[Before_678.density])*100
	Travel Time	PerD_ttime: (([After_678.ttime]-[Before_678.ttime])/[Before_678.ttime])*100

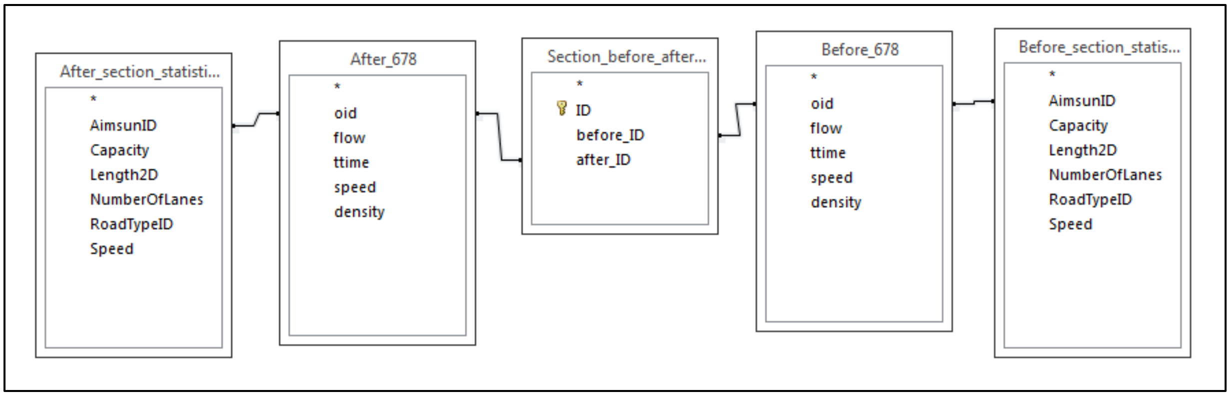


Figure 30. Access association structure.

Each of these variables must be interpreted separately since positive and negative shifts for each suggest different trends. In terms of speed, if the absolute difference and percent change are positive, this would show that the section may have improved slightly so that more vehicles are able to move freely or there is less congestion. On the other hand, positive absolute difference and percent change in density or flow would show that the section became more crowded. A positive change for travel time would show that it took vehicles longer to get through the section after the Green line was implemented.

One important assumption within this simulation model was the size of the microscopic region surrounding the Green Line LRT corridor. The research team opted to include University Avenue, Interstate 94, and parallel alternative routes just to the north and south in order to capture the possible diversion of drivers away from University Avenue.

As seen in Figure 31 below, this assumption is reasonable. The figure, showing changes in speed for the morning peak hour period (demand 8, 7:30 to 8:30 AM), includes relatively cohesive changes along University Avenue, Interstate 94, and Washington Avenue, and to a lesser extent some of the crossing arterials such as Snelling Avenue or Highway 280. Outside of the mesoscopic region, these changes become less coherent as the simulator attempts to converge to a dynamic path choice equilibrium.

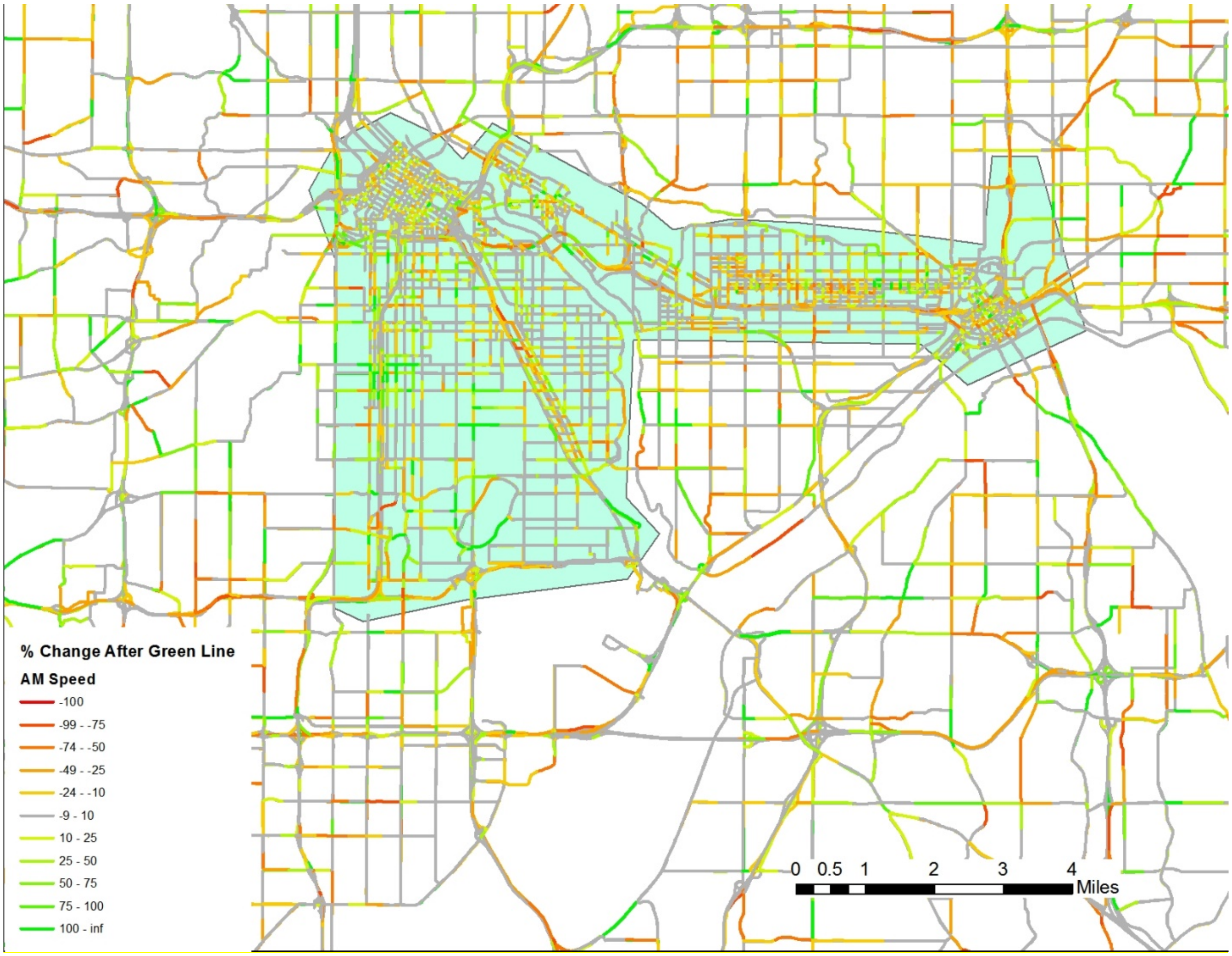


Figure 31. Change in Speed from before and after of hybrid model (Microscopic Region shaded).

Figure 32 presents a view of the level of congestion, as expressed by critical density around 45 veh/mile, during the Morning peak. As can be seen there are few changes after the implementation of the Green Line. The area of Dale Ave north of University is more congested as are parts of I-94. A detailed view of the area around I-94 between Snelling and down town St. Paul shows that I-94 is taking considerable more traffic and the speeds have dropped greatly. Basically, the preexisting bottleneck at the commons with I-35E is getting worse due to the extra demand displaced from University Ave.

A different view of the same result can be seen in Figure 34 where the % difference in flow and density before and after the introduction of the Green line. Figure 35 shows the same for speed.

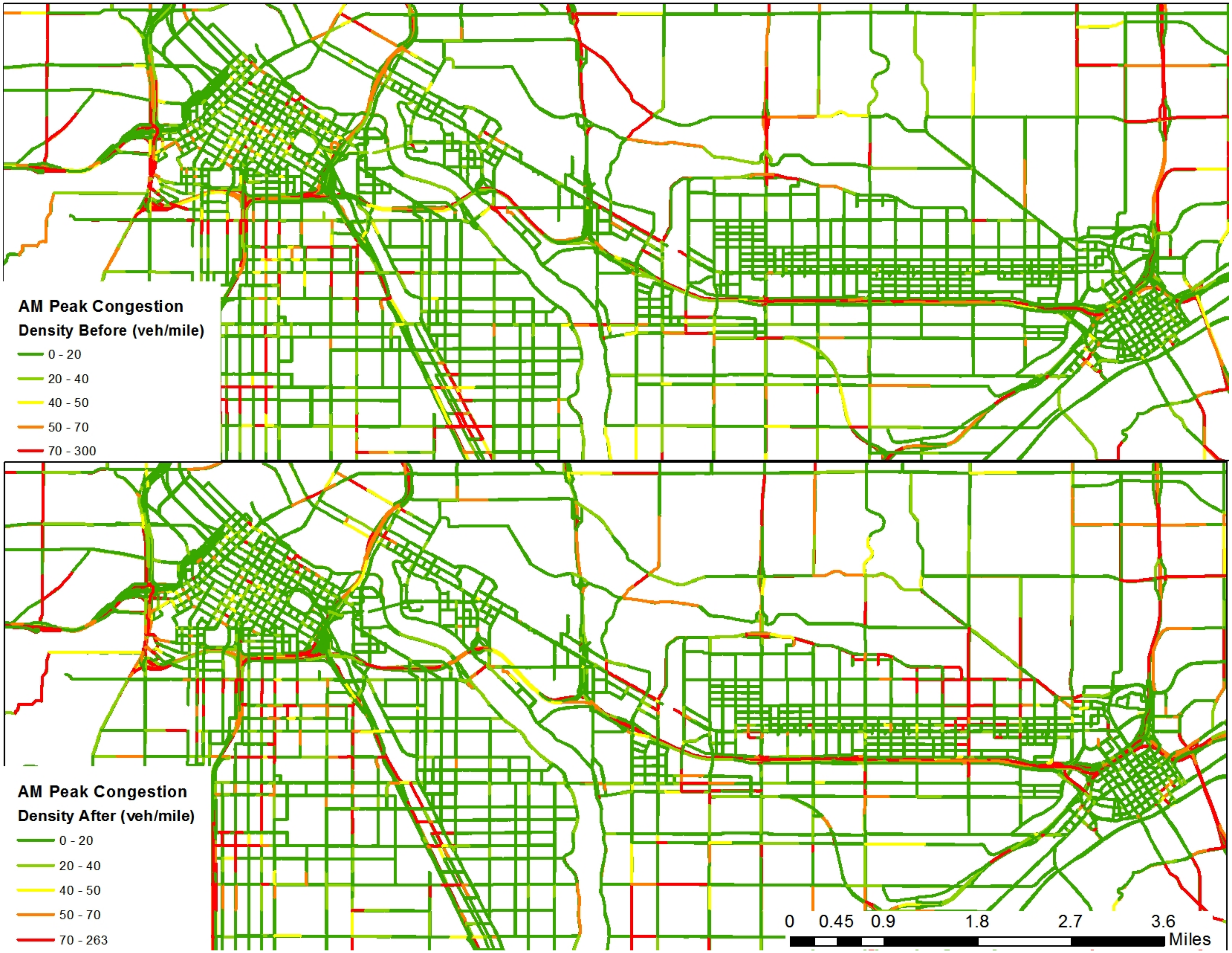


Figure 32. Change in density by link for demand AM Peak (6:45 - 7:30 AM).

Figure 33. Congestion changes along I-94: AM peak (6:45 - 7:30 AM).

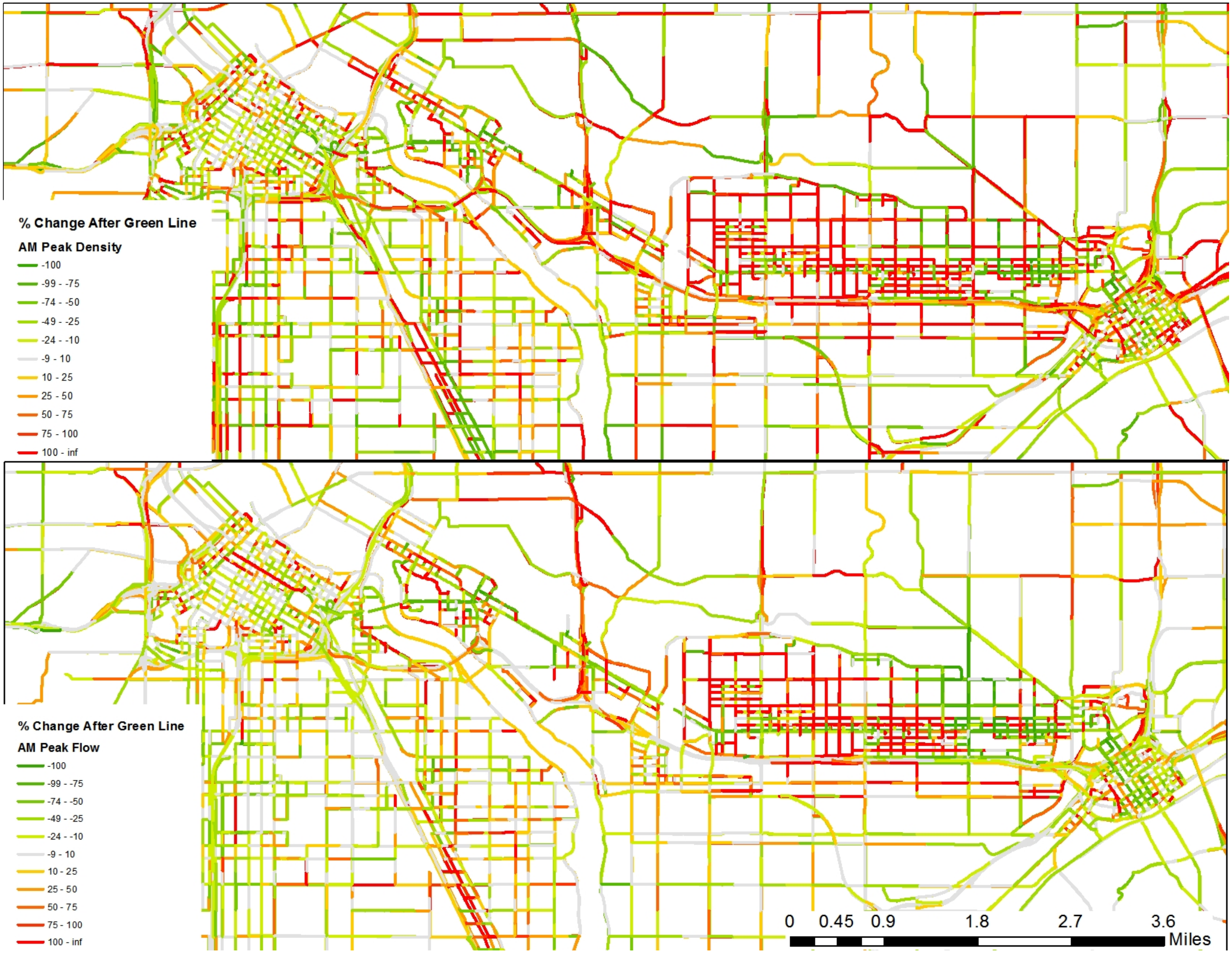


Figure 34. Percent (%) Changes in Flow and Density without and with the Green Line LRT during AM Peak (6:45 - 7:30 AM).

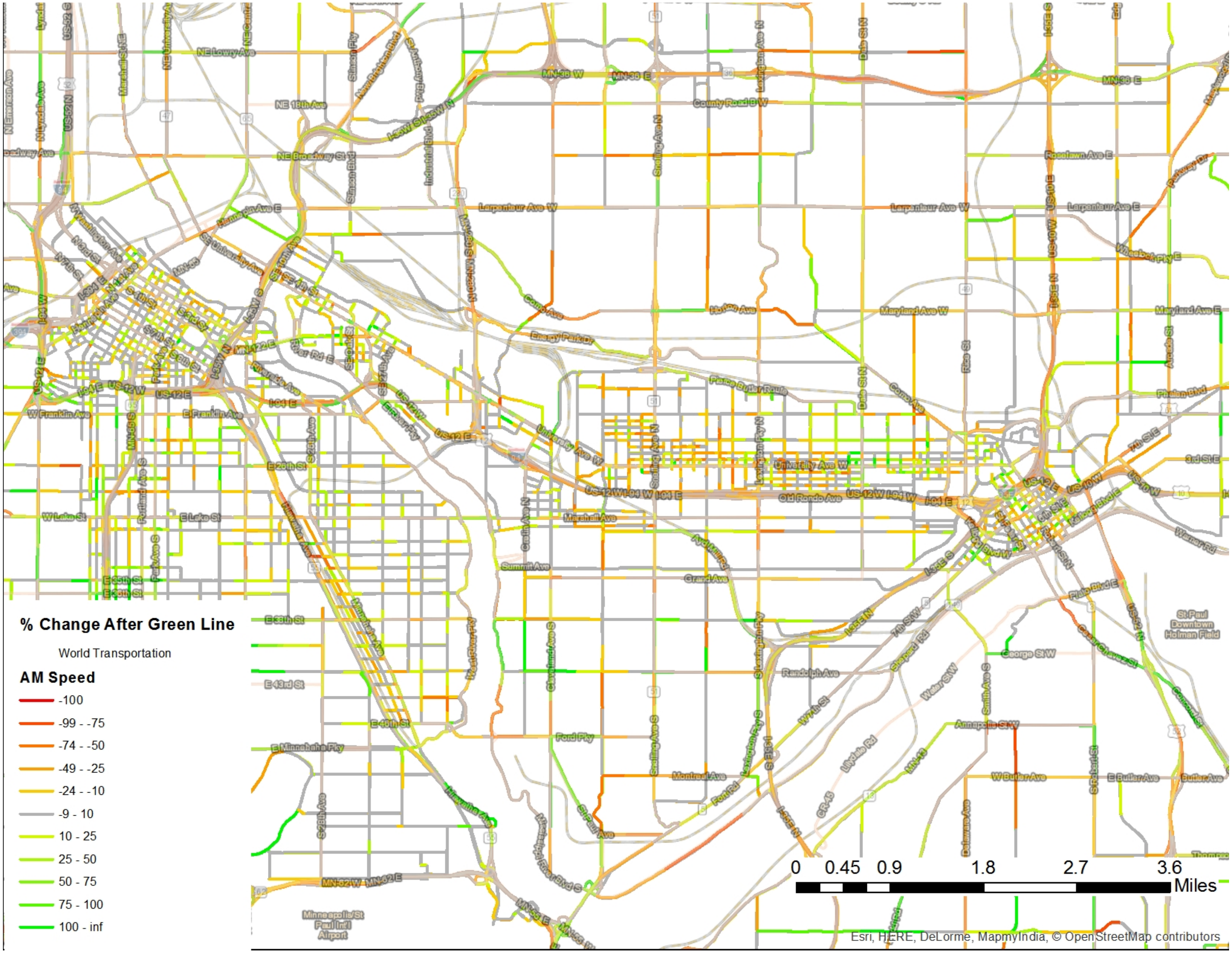


Figure 35. Percent (%) Changes in speed without and with the Green Line LRT during AM Peak (6:45 - 7:30 AM).

The results indicated above are similar to those observed during the afternoon periods. As can be seen in Figure 36 and Figure 37 the congestion of alternative routes around University Ave increased. I-94 absorbed most of the extra traffic and became more congested as a result. The PM peak period also varied slightly from the AM peak in the fact that many of the neighboring roads directly adjacent to University Ave became more congested. The PM results also varied greatly along the section of University Ave between Lexington Parkway and Dale Street. After the Green Line was implemented, University Avenue sections had density's less than the critical density of 45 veh/mile during AM peak, while in the PM they were heavily utilized with sections having 70+ veh/mile.

The effects of these density increases can be seen more clearly in Figure 38. The figure shows areas that increased in density and flow after the Green Line implementation in red. It is notable that I-94 increased in congestion and consequently had a reduced flow due to that increase. The same effect is also seen on the majority of the University corridor between the Minneapolis and St. Paul downtown cores. It should also be noted that due to the closure of Washington Ave through the University of Minnesota Campus traffic had to be rerouted and is seen as increased density near 35W along 4th Street and University Ave.

In conjunction with these changes in density and flow, shifts in speed were observed. From the increased demand, Interstate 94 experienced decreases in speed across the majority of its length (see Figure 39 below). Red links in the figure represent significantly slower speeds, while green links are higher speeds after the Green Line is implemented. Although there appears to be changes all over the network many of these "cancel" each other out due to the nature of the simulation attempting to find the most optimal solution. In other words there is a visible balance between green and red links further away from the study area.

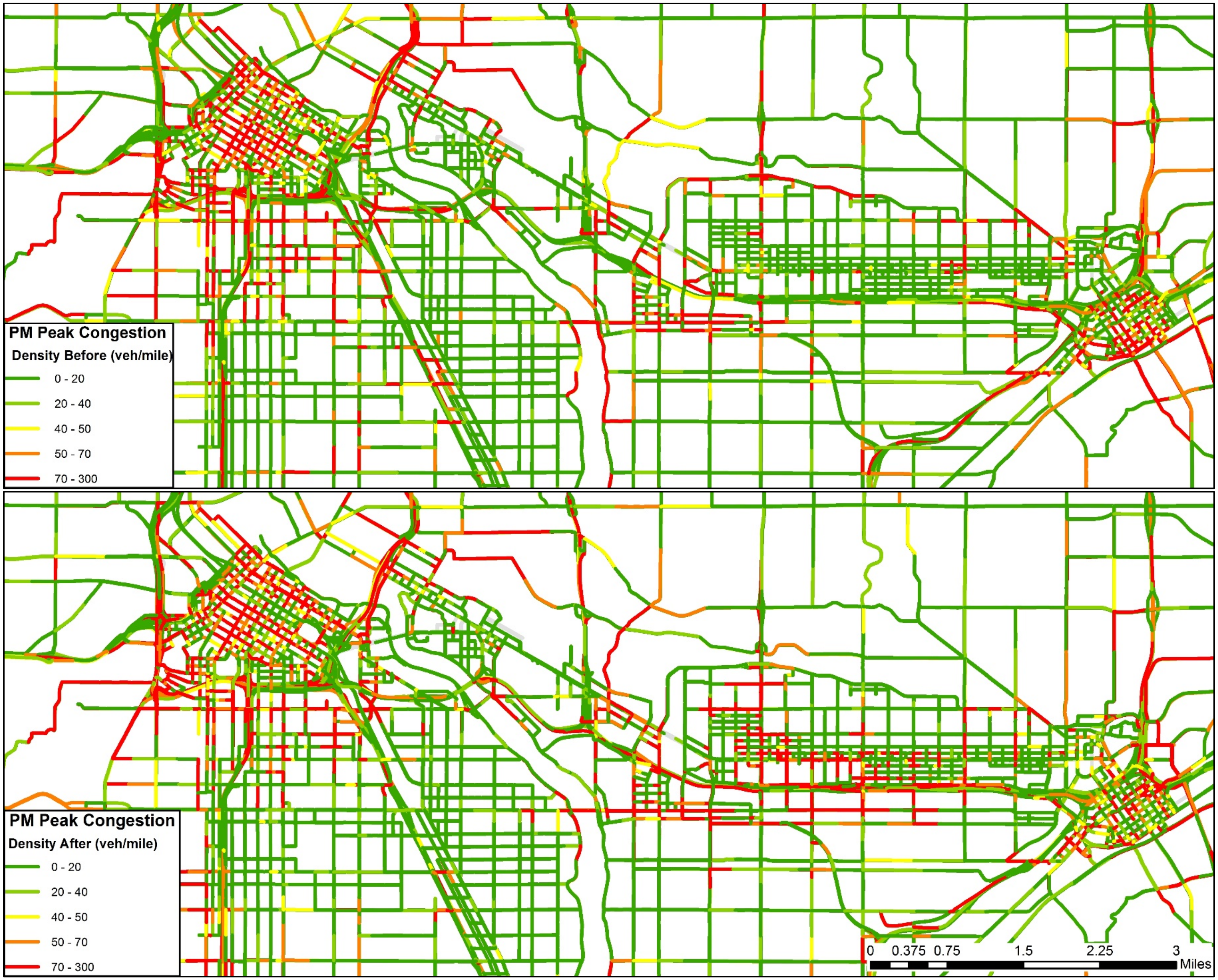


Figure 36. Change in density by link for PM Peak (3:00 - 4:00 PM).

Figure 37. Congestion changes along I-94: PM peak (3:00 - 4:00 PM).

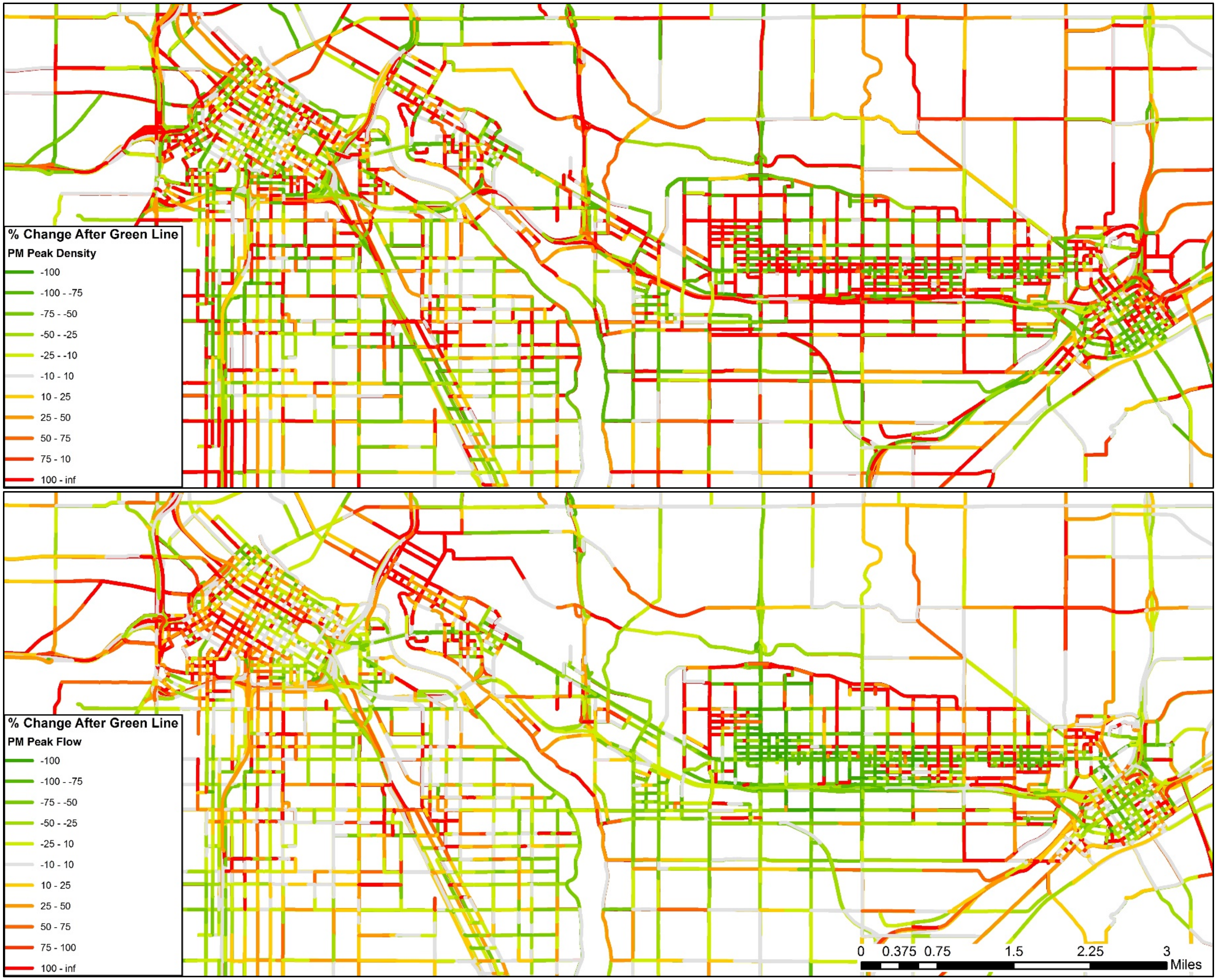


Figure 38. Percent (%) Changes in Flow and Density without and with the Green Line LRT during PM Peak (3:00 - 4:00 PM).

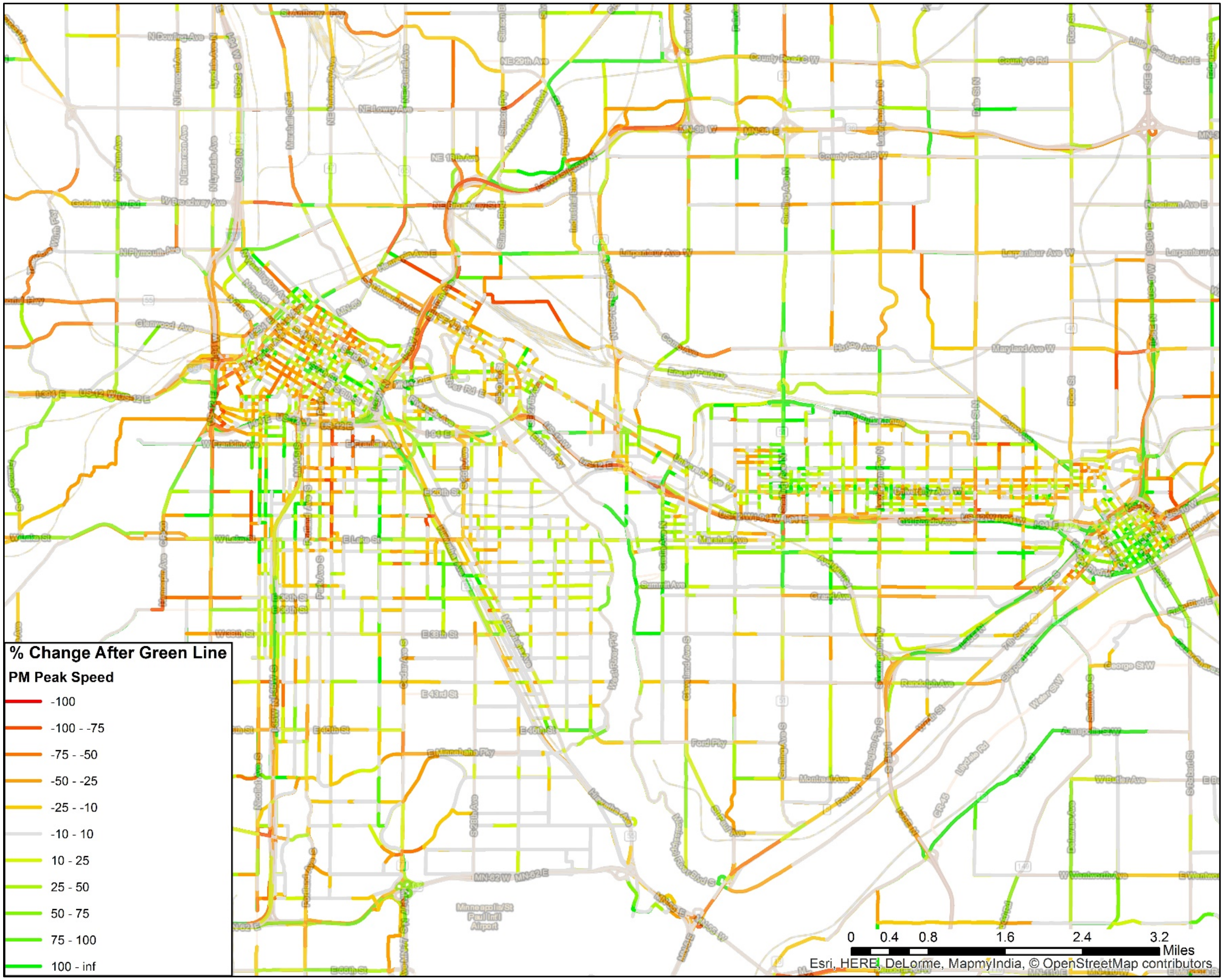


Figure 39. Percent (%) Changes in speed without and with the Green Line LRT during PM Peak (3:00 - 4:00 PM).

While the results above are representative, they are samples from the entire set of simulations completed for this task. To aggregate the results somewhat, the travel times for the entire University Avenue corridor were determined, on average, for each period within both the Before and After models. Table 12 below shows the travel times for eastbound and westbound traffic along University Avenue between Huron Boulevard in Minneapolis and Robert Street in Saint Paul and Figure 40 shows the boundaries of the corridor used.

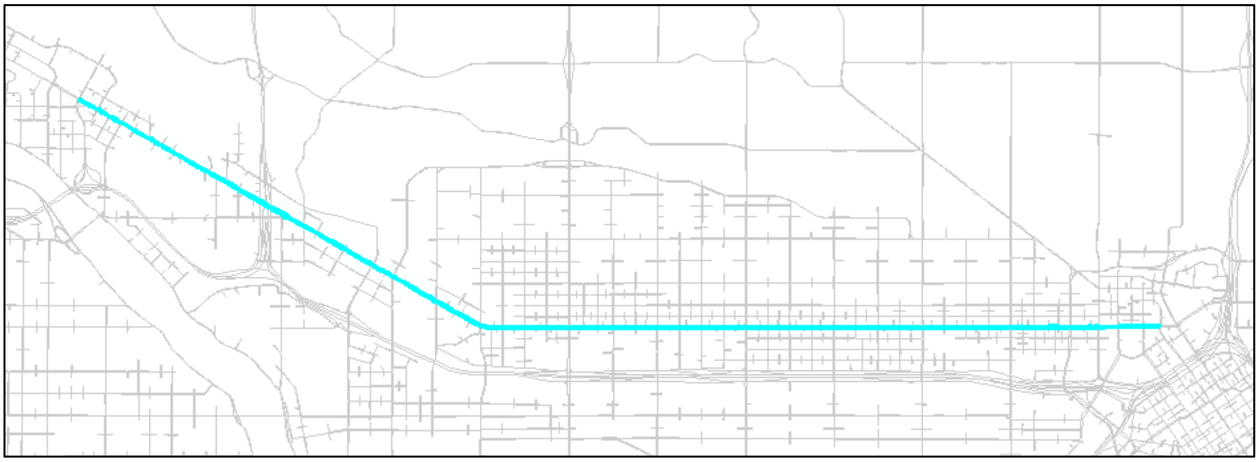


Figure 40. Path used for vehicle travel time estimation.

Table 12. Travel times between Huron Boulevard and Robert Street.

		Eastbound		Westbound	
Interval	**Time**	**Before**	**After**	**Before**	**After**
6	6:00 - 6:45	676 (s)	1043 (s)	376 (s)	1093 (s)
7	6:45 - 7:30	699 (s)	1125 (s)	272 (s)	1379 (s)
8	7:30 - 8:30	728 (s)	1138 (s)	754 (s)	1342 (s)
15	2:30 - 3:30	744 (s)	1110 (s)	424 (s)	1330 (s)
16	3:30 - 4:30	749 (s)	1237 (s)	278 (s)	1301 (s)
17	4:30 - 5:30	908 (s)	1389 (s)	808 (s)	1557 (s)
18	5:30 - 6:00	819 (s)	1457 (s)	480 (s)	1842 (s)

As seen in the table, travel times increased along University Avenue in the after model. Closer examinations of these travel times show that the signals along University Avenue were much more optimized for vehicle traffic prior to the implementation of the light rail. As such, especially when volumes were low, travel times were small. With the Green Line implemented, the signals prioritize the light rail and, when that is taken care of, clearing side streets. This causes the mainline vehicles to encounter queues more frequently than before and incur greater delays.

5.3 Green Line Travel Time – Takeaway for Light Rail Transit Modeling

During the course of this project two separate and equally challenging light rails were programed into the model. The two lines both operate in very different ways when consideration is given to the signals and side streets they cross. The Blue Line (Hiawatha) was, from the beginning, a preempted corridor. After the train left the downtown area of Minneapolis all signals and cross streets the train was to cross were preempted so the train had the right of way before it arrived. This is in contrast to the Green Line which only has a few isolated preempted lights of which all are near the University of Minnesota, the rest were programed as LRT priority. Where LRT priority is defined as the signals will extend the complimentary thru green phase or place a call to begin the LRT phase following any conflicting phases.

Both of the LRT lines have gone under extensive signal retiming from when they were first introduced. Since the project was started well after the Blue lines completion in 2004 the effects of the full preemption plans initially used were known. When the line first starting running in 2004 with the signal controllers and detectors installed it was seen that they were not adequate for the task. The preemption combined with the old signal controllers resulted in movements being called for no vehicles and cycles starting over after every preemption this combined with the peak hour headway of trains at 7.5 minutes and cycle lengths near 250 seconds would gridlock side streets. Engineers quickly had to come up with a way to mitigate traffic congestion and were able to mitigate some but not all of the delays experienced. They were hindered by the technology of the time and then in 2012 through the use of new techniques, detectors expansion, and update signal cabinets specifically designed for LRT interaction they were able to decrease the congestion.

The Green Line has gone through many iterations of signal retiming. For this project the initial timing were provided in January of 2014. These timings were at the time the most reasonable assumption for how the light rail was going to run. It was found out later that during the initial testing the signal timings were changed drastically in hopes of avoiding the same sort of situation that occurred when the Blue line first opened. Even as this project was finishing the timings were still be changed on a nearly weekly basis. The reason they could not simply copy the same timing scheme used on the blue line was due to the previously mentioned fact that the green line was not a fully preempted corridor. The signals were operating under a LRT priority which did not always work as intended and without preemption the trains have to stop at every red light. This was evident in the first few days of operation as the travel times were significantly greater then what was scheduled due to the excessive stopping at the 40+ intersection it crosses.

Table 13: Green Line Average Travel Times for Completed Trips by Period

Interval	Time	Eastbound		Westbound	
6	6:00 - 6:45	3858 (s)	64.3 (min)	3443 (s)	57.4 (min)
7	6:45 - 7:30	3775 (s)	62.9 (min)	3913 (s)	65.2 (min)
8	7:30 - 8:30	4049 (s)	67.5 (min)	4299 (s)	71.6 (min)
15	2:30 - 3:30	2965 (s)	49.4 (min)	3135 (s)	52.2 (min)
16	3:30 - 4:30	3034 (s)	50.6 (min)	3174 (s)	52.9 (min)
17	4:30 - 5:30	2939 (s)	49.0 (min)	3147 (s)	52.4 (min)
18	5:30 - 6:00	2568 (s)	42.8 (min)	3145 (s)	52.4 (min)

As indicated in Table 13, travel times range between roughly 45 and 75 minutes. Morning travel times are longer across all scenarios and in both directions, with an average just under 65 minutes either way. The westbound trains also experience significant differences in travel time by period, much more so than other scenarios. In the afternoon, both directions show remarkably stable travel times at roughly 50 minutes. The fastest travel times range down to just under 45 minutes, which would likely be close to the travel time during off peak conditions.

5.4 Convergence of Aimsun Loop

The loop with Voyager as described in Figure 11 converged very quickly in terms of demand change. Within only 4 iterations of the loop with Voyager the demand change was already changing by only 0.16% for a given particular trip and only 0.0052% of the total demand. Given that each one of these loops was taking on the order of 3-4 days to complete this was seen as sufficient for convergence.

5.5 Mode Shift

After several iterations with Voyager the total number of trips during morning peak and mid-day off peak were tabulated for each mode and each iteration. The original values and change loop-on-loop are presented in Table 14. Note that the results from the first loop are omitted due to a report generation error.

Across both periods, all non-SOV types experienced decreases in mode share; this was most severe for HOV vehicles during morning peak. The hybrid model predicted generally higher link speeds than the RPM, resulting in a shift toward driving and away from transit alternatives. The total change to the light rail corridors represent a roughly 7.4% and 4.6% decrease in ridership during morning peak and midday off peak, respectively. It was found that the majority of these trips were short trips from centroids that were geographically located near each other. That is trips that would only use a few links in the network to reach their destination. This again is likely from the fact that our link speeds were faster then what the RPM produced which made these short SOV trips better than the alternatives.

Table 14: Summary of mode shift by iteration

PEAK PERIOD (6:00 AM - 8:30 AM)							OFF PEAK (8:30 AM - 2:30 PM)				
RPM Original *(Trips)*	Δ Loop 0-2	□ Loop 2-3	□ Loop 3-4	□ Loop 0-4			RPM Original *(Trips)*	□ Loop 0-2	□ Loop 2-3	□ Loop 3-4	□ Loop 0-4
541,746	-287	180	-10	-117	Pedestrian		493,916	-261	42	1	-218
173,453	-797	498	-18	-317	Bicycle		145,999	-731	71	-3	-663
3,523,018	20,497	-1279	47	19265	SOV	*(1 Occ.)*	3,253,911	1,187	-97	2	1092
834,676	10,024	-138	45	9931	SOV	*(2 Occ.)*	951,951	471	-31	1	441
1,750,852	18,158	47	92	18297	SOV	*(3 Occ.)*	2,055,451	719	-32	-1	686
36,278	-15,769	-226	-38	-16033	HOV	*(2 Occ.)*	249	-249	0	0	-249
56,695	-24,516	-490	-82	-25088	HOV	*(3 Occ.)*	452	-446	0	0	-446
82,491	-1,752	374	-3	-1381	Local Bus	*Walk*	26,217	-345	24	-2	-323
11,249	-412	96	-3	-319	Local Bus	*PNR*	2,711	-53	4	0	-49
5,466	-172	36	0	-136	Local Bus	*KNR*	550	-10	1	0	-9
42,232	-2,119	402	-15	-1732	Express Bus	*Walk*	2,277	-63	6	0	-57
14,758	-1,222	261	0	-961	Express Bus	*PNR*	782	-25	3	0	-22
4,156	-261	49	-2	-214	Express Bus	*KNR*	76	-2	0	0	-2
13,448	-1,073	153	-11	-931	Light Rail*	*Walk*	3,801	-180	11	0	-169
1,866	-204	26	-3	-181	Light Rail*	*PNR*	187	-12	1	0	-11
935	-97	13	-1	-85	Light Rail*	*KNR*	62	-5	0	0	-5

* Blue and Green Lines both included

6. Lessons Learned

This project involved a number of challenges and exploration of uncharted territories. To this day there are only a handful of examples of integration between a Travel Demand Model and a Dynamic Traffic Assignment and in all those cases the DTA part was handled with simulation applications that cannot realistically emulate complex traffic control systems. Only one other model, New York City, has utilized the power of hybrid simulation in a scale similar to the one covered in this project. The common factor in many of the issues encountered was size. The size of the required network disqualify all traditional methodologies for constructing, calibrating, and even running a simulation model. The following sections draw together information scattered throughout this document and try to distill from them the lessons learned during the effort in this project. The sequence followed is the same one followed during the project; constructing, calibrating, running the model, and interpreting the results.

6.1 Constructing a large scale simulation model

6.1.1 NETWORK GEOMETRY AND CONTROL

Traditionally, traffic modelers build simulation models by hand. Using aerial imagery as the background, they trace the links and nodes in the study area. In a large scale simulation project this is not feasible. The model in this study has upwards to 25,000 links. The only feasible course of action is to import the network from another source, therefore it is imperative that such a source is located and evaluated for its compatibility before the start of the project. There are several sources of digital maps of the road network each having its own level of resolution and information attributes. The effort involved in importing the geometry and bringing it up to a state that is usable by the selected simulation application, Aimsun in the case of this project, is far from trivial and needs to be planned and budgeted for accordingly.

In the case of this project, the source of the network geometry was the GIS representation of the RPM. This representation provided all link and nodes that are considered important for the purposes of travel demand estimation with static traffic assignment. This resolution is not sufficient for the areas of the network where dynamic traffic control systems have a great influence on traffic conditions. For the purposes of this project the initial geometry import was enhanced through the traditional manual methods. It was estimated, possibly in error, that the effort of increasing the resolution for a part of the network would require an amount of effort compatible with the project resources. The task was more demanding than originally anticipated and this is an experience this project is providing to future efforts of the same kind. One particular aspect of the efforts involved in constructing the geometry was the generation of the correct intersection layouts, with left turn pockets, free right turns, the location of the stop lines, and other such details. This effort would have been considerably reduced if the geometry was imported from a digital map that already contains such information.

A similar lesson applies to the description of the traffic control systems included in the high resolution area of the model. Although in most jurisdictions a traffic signal optimization program is used to develop traffic signalization patterns, this information is rarely ultimately stored in a convenient container. Although the profession has evolved beyond handwritten forms, it should be understood that a PDF of the signal timings for an intersection is as useful to a traffic modeler as a handwritten note. Digital doesn't mean compatible. Most simulation applications have included functionality to allow the importation of traffic signal plans from software like Synchro and TP+. Unfortunately, given that in some cases these are competing companies, this integration is not complete. Regardless, in the case of this project the only source of traffic control information was on paper, with minor traffic control elements like stop and yield signs being located manually with the help of Google Street View. One other reason to stress the importance of digital records of traffic control plans is that such plans change very often especially in the case of a before and after study where the after at the time of the project is only a design on paper. It is almost guaranteed that these plans will change as soon as the new construction opens to public use increasing the effort of maintaining an up-to-date simulation model.

6.1.2 RUNNING THE SIMULATION

Parallel development

One of the biggest challenges of building a network of the size and scope of this model was the idea of concurrent development. It was found that if only one person was able to work on the model at once there would be no way to complete it in a reasonable time. To overcome this obstacle the areas of interest around the two LRT lines were split into two separate networks. Each network could then be worked on by a different researcher. Given the size of the small networks, they could be run on more modest workstations and complete runs in minutes. As will be mentioned the entire hybrid simulation model takes hours/days to run and would be impossible to calibrate with any of the common practices.

For the purpose of this project only the two LRT line corridors were singled out for extensive calibration effort. During the course of the project however other related projects using Aimsun that involved calibrating microscopic potions of freeways were used in the model as well. These pieces were inserted into the model as they became available since their level of detail was better than the Regional Planning Model stick network they were replacing. Each one of these new pieces helped to create a more cohesive model that better represented the network for the purpose of the Hybrid simulation.

This parallel development worked well in the original Aimsun 7 versions since the networks had a tool for directly importing another Aimsun network. However, in Aimsun 8 the tool was removed since it did not work properly. It was found that geometric attributes can be copied and pasted into another network but all signal, bus line, or other elements that are not stored in the feature class were lost. This became a problem later since the Green line signals and geometry were programmed in a very small network containing only the sections impacted by the construction and were to be imported into the main network. After contacting the developers (TSS) they helped in constructing a script to export and subsequently import the signal data into our new model. It should be mentioned that Aimsun 8 now has a feature called "Revisions" which allows a base network to be specified and then have revisions built off and reconsolidated into the base at a later date. While this feature was not used in this project it is nevertheless a key feature when determining if "cutting" the network into smaller pieces is a viable option.

Running a large traffic model

STEP 1: MACRO ASSIGNMENT PATHS

A possible first start to help a hybrid DUE or any DUE reach convergence faster is to use the results of a static assignments to provide an initial first set of paths for the DUE. Since macro assignments are much quicker in terms of computational time they can help reduce the overall run time of the final DUE. The down side to using this technique is that the model needs to be calibrated for a macroscopic model and a mesoscopic model since both use different methods of distributing traffic. In our case the model was derived from the macroscopic RPM model and thus had most of the parameters already set. In our case it was found that the added steps of running the macroscopic model, exporting the paths and importing them into the Hybrid DUE took more time to execute than would be saved from running the Hybrid DUE without supplying paths. This technique can be useful when the demand does not change between runs and the Hybrid DUE is being calibrated since the macroscopic parameters do not affect the hybrid DUE, thus allowing a jump start into each run.

STEP 2: RUN SUCCESSIVELY EACH PERIOD AT INCREASING DEMAND LOADS

If a particular demand period is difficult to run, a potential way to mitigate it is to load only a portion of its demand. This iterative solution could be refined depending on how congested the network is. For example in this project Demand 8 (7:30am – 8:30am) is highly congested. A DUE run with only 50% of the demand can be run and the paths from it can be saved so they are loaded into the next simulation which would be 75% of its own demand. This methodology could be used to make as many “steps” as needed before loading the full 100%. The main drawback to this solution is the additional time it would take to do this iterative approach.

STEP 3: SINGLE TO MULTIPLE PERIOD SIMULATIONS

A technique that was used for this project in order to more accurately handle the large demand of the peak period was to run multiple periods together as one and only keep the results of last intervals that correspond to the period of interest. Previously, the successive interval periods were run individually of each other. This caused issues since the traffic state at the end of each run could not be saved and imported into the next therefore cars that entered towards the end of the simulation would still be on the road when the simulation ended. This resulted in the congestion caused in one period to not be successively moved to another period and low capacity side streets to be over utilized. While a warm up period can be specified it used the same demand as the interval that was running so in the case of peak periods this would not catch the increase in demand over time that would normally occur.

When a comparison of the demand 8 (7:30am-8:30am) was run and compared to the demand 6, 7, and 8 (6:00am-8:30am) the results showed that vehicles during the period of interest (7:30am-8:30am) moved at more reasonable speeds and density’s given the time of day. As can be seen in Figure 41 which shows the percentage change in density where red indicates an increase in density of the 3 period run over the single period run. The exact queries are similar to those seen in Table 11 where the after in this case is for demand 6,7,8 and before is the single period 8 demand. It can be seen that the densities on major highways and arterials have increased now that the vehicles from 6:00am – 7:30am are more accurately represented.

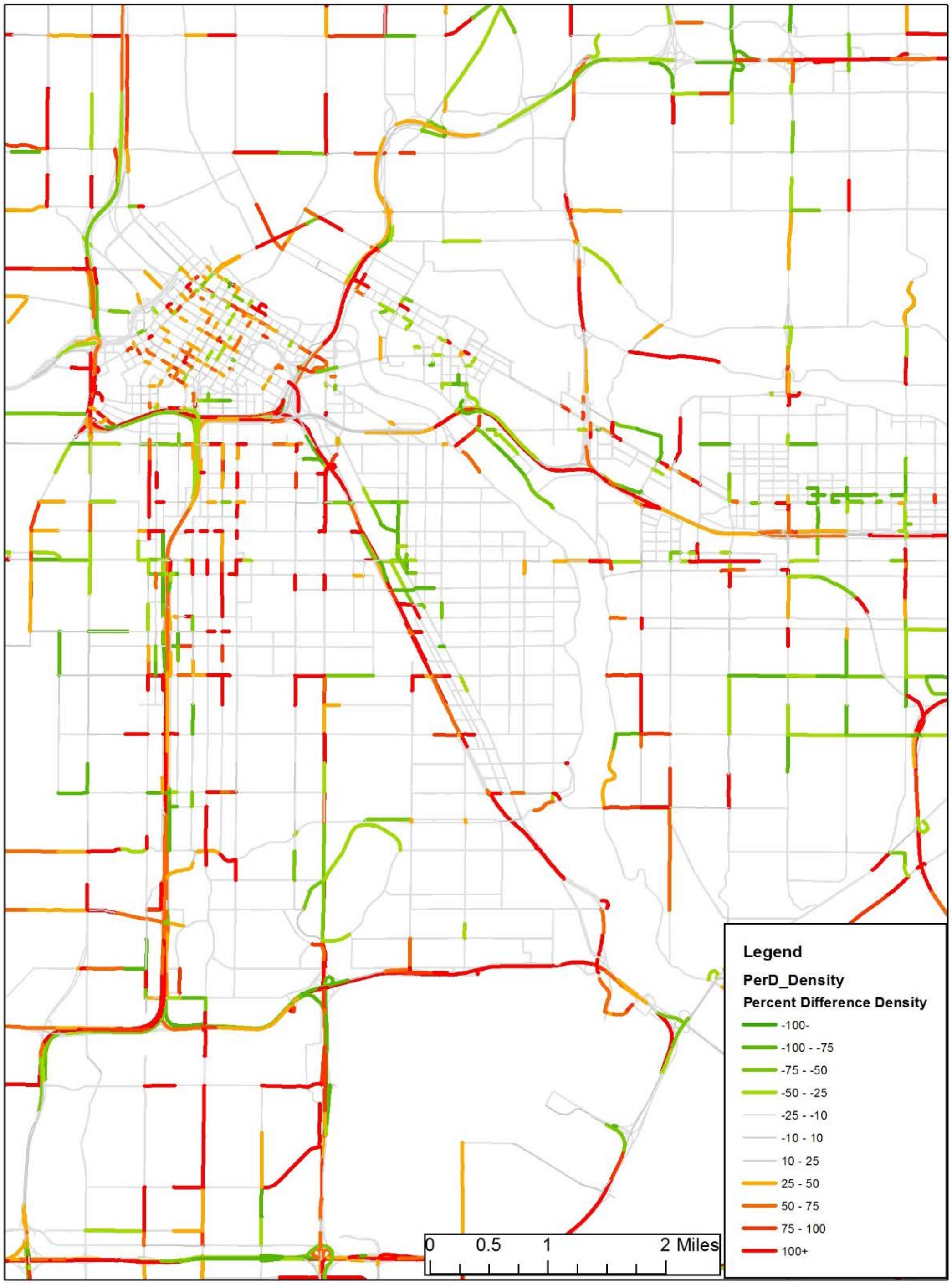


Figure 41. Density comparison of multiple period simulation vs single period simulation[1]

[1] Sections with density's less the 25 vehicles/km/ln were omitted from the results

6.1.3 CALIBRATION

As mentioned previously the effort required to calibrate a network the size of the Twin Cities metropolitan area is extensive. Unless the engineer has unlimited resources and the availability of programmers to be working on the network 24/7, there comes a time where the network needs to be calibrated on a global scale. While a partial calibration was done in this network during the final stages of the project other methods were considered and hypotheses were developed on how to calibrate the network on a global scale.

One such hypothetical method came out of a clarification received from the developers of Aimsun on how vehicles behave in the mesoscopic region. It was found that the vehicles follow a simplified form of the fundamental diagram defined by:

$$Q(k) = min\left(Vk, \frac{1 - Lk}{R}\right)$$

where Q = Flow, V = Speed Limit, k = Density, L = Effective Vehicle Length, and R is Reaction Time. This, when converted to Aimsun parameters, is:

$$Q(k) = min\left(Vk, \frac{1}{R}\left(1 - \frac{k}{k_{jam}}\right)\right)$$

With this information it can be seen that the equation solves the flow for a given section knowing its density. Since the Speed Limit (V) and Jam Density (k_{jam}) are set by physical parameters of the roadway, the only useable variable left is the reaction time in order to affect the flow of a section. This fact was used to some extent earlier on to calibrate each section's maximum flow using the equation above, reaction time, and the capacity produced by Voyager and the Regional Planning Model. While this method did work somewhat it introduced other problems that needed to be corrected.

A refined version of this was more complicated since the parameters were not readily available inside Aimsun. It was hypothesized that if ADT (Average Daily Traffic) and freeway detector data were used to obtain peak flows on every link then the above method we used could provide a more accurate representation of reality than the capacities produced by the Voyager model.

Validation Data

On a note similar to geometric and signal control data, having access to uniformly-collected and digitally stored freeway and arterial traffic data is critical to calibrating and validating large scale models. For this project, significant data was available for all freeways and was provided in a convenient and robust format. Contrarily, turning movement data along arterials were available only in limited and often inconvenient forms, such as PDF copies of turning movement count sheets. As was stated before, coalescing such data into a single repository which contains data in a unified format would greatly enhance both the usability and value of collecting such data.

6.2 Computational Effort

One of the biggest lesson during this project was the amount of computational effort required to run a simulation of this size. While performing the Macro Validation the computer requirements were low and usage was low. Some of this is assumed to be due to the fact that the original model was designed for macroscopic simulation. Therefore the scope and network geometry was coarser then compared to the final project.

The computational/time effort started to increase dramatically once calibration of the micro areas began. Prior to Aimsun 8 many operations were not multi-threaded and the option for multi-threading was not available. Therefore the two sub-networks described earlier individually required 25% of real time to simulate the equivalent simulation time to run (15min real time for 1 hour simulation time). This required us to modify our original plan of modeling the whole 24 hours down to just peak hours.

Once both models were combined into a single Hybrid model, the true computational requirements and time revealed themselves. Table 15 shows the requirements of the peak periods in the two Hybrid simulation models. Even with the majority of statistics off the model was using upwards of 150GB of RAM. These types of requirements require special computers to achieve such limits. Since Aimsun 8 only allows a maximum of 8 threads this also proved a unique challenge since most computers with enough RAM are based on getting as many threads as possible even at low clock speeds. Therefore to decrease computation time while still maintaining the appropriate amount of RAM, processors with minimal cores and high clock speeds were used to build computers specifically for this task.

Table 15: Computation Requirements of Hybrid Model

		Pre Green Line Network			Green Line Network		
Demand Interval		**RAM (GB)**	**Iterations**	**Run Time (hr)**	**RAM (GB)**	**Iterations**	**Run Time (hr)**
6	6:00-6:45	17.5	4	1.6	24.2	5	1.7
7	6:45-7:30	49.5	13	4.3	55.5	14	7.1
8	7:30-8:30	116.6	24	20.5	88.7	19	14.0
15	14:30-15:30	65.1	13	8.8	70.1	13	9.9
16	15:30-16:30	125.1	25	19.1	85.1	16	14.9
17	16:30-17:30	118.0	25	21.9	148.1	25	22.5
18	17:30-18:00	38.0	16	7.2	40.2	14	9.2
Multi-Demand							
6-8	6:00-8:30	291	27	92.2	261	26	86.1
16-18	15:30-18:00	356	27	114.14	331	25	78.7

6.3 Result Visualization

The process of visualizing the results from the various simulation runs uses two main programs, ArcMap, and Access. Access is used to both query the database and clean the data for importation in to ArcMap for visualization. While ArcMap could potentially be used directly with the database it was found to be unstable, so using Access to get the data into an acceptable format was found to be more efficient.

It was also found that the simulation outputs so much information that it is impossible to visualize it all at once. Given this challenge, a way of consolidating the data into useful info was derived. From the available data it was found that the most useful data was the percent and absolute differences between Speed, Flow, and Density. These were calculated and displayed for the peak periods and analyzed to examine the differences.

In Access a connection is set up to the database and static attributes about the networks are imported. The static attributes of sections include parameters such as speed limit, length, capacity, and number of lanes. Other data imported are section maps to correlate the sections that changed between the before and after green line implementation to ensure that the data matches between each network and so calculation between the changes could be made between the two scenarios. Access also cleaned the data of unrealistic values such as speed of -1 when no vehicle was registered going through a section during a detection interval.

With the clean data from each of the peak demand intervals before and after statics such as percent and absolute difference between before and after green line implementation were calculated. These results were correlated so that they could be visualized in ArcMap. To visualize ArcMap needed to have the clean data and “links” to associate them with. The section links needed for ArcMap are automatically generated by Aimsun through the network export tool in the form of shape files. Both the text files and shape files are imported into ArcMap and can be joined so that they can be colored based on their values. An example of this procedure can be seen in Figure 42 which is a zoomed out version of the maps used in the result section.

In summary the generation of the results is as follows:

1. Run simulations and note run ID’s
2. Run access queries with the before after ID’s
3. Export the text files as comma separated files
4. Import the section GIS into ArcMap
5. Import text files into ArcMap
6. Adjust the view styles to represent what is needed

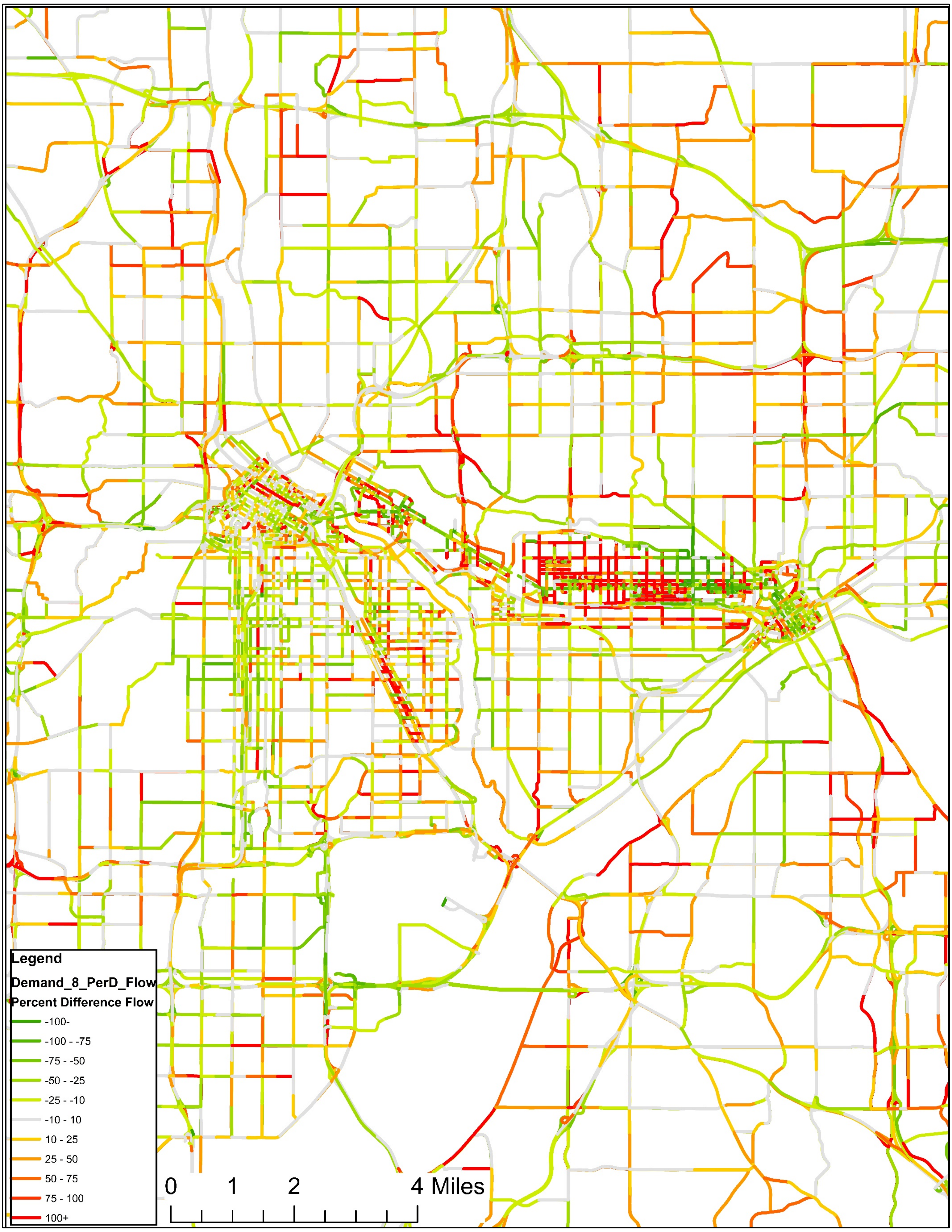


Figure 42. Results fabrication example for inner metro region

References

(1) M.D. Anderson, and R.R. Souleyrette "Pseudo-dynamic travel model application to assess traveler information." *Transportation*, Vol. 29(3). 2002.

(2) R. Tung, Z. Wang, and Y. Chiu. "Integration of Dynamic Traffic Assignment in a Four-Step Model Framework – A Deployment Case Study in Seattle Model." in *3rd Conference on Innovations in Travel Modeling* (ITM), Arizona. 2010.

(3) Cambridge Systematics. *SHRP C10B: Partnership to Develop an Integrated, Advanced Travel Demand Model and a Fine-Grained, Time-Sensitive Network Model Design Plan*. (Draft Report). 2010.

(4) W. Burghout, and J. Wahlstedt. "Hybrid Traffic Simulation with Adaptive Signal Control." *Transportation Research Record*, Vol. 1999. pp 191-197

(5) E. M. Bent, R. Hiatt, and K. Singa, "Full-Featured Bus Rapid Transit in San Francisco, California: Toward a Comprehensive Planning Approach and Evaluation Framework." *Transportation Research Board*, Vol. 2072. 2008.

(6) Cambridge Systematics. "34th Street Transitway/Manhattan Traffic Model." http://www.nymtc.org/project/BPM/BPM_UserGrpMtgs/2011%20Meetings/MTM%20for%20NNYMT%2002092011.pdf (Presentation). 2011. Accessed May, 2014.

(7) Transport Simulation Systems. *Aimsun 8 Dynamic Simulators Users' Manual*. Software Manual. Transport Simulation Systems, Barcelona, Spain. July 2014.

(8) B. Ran, and D. Boyce. *Modeling Dynamic Transportation Networks* Berlin: Springer-Verlag. 1996.

(9) B. N. Janson. "Dynamic Assignment for Urban Road Networks", *Transportation Research. B*, 25(2-3): 143-161. 1991.

Appendix A

Centroid Connector Script

```
centroidType = model.getType( "GKCentroid" )
centroidList = model.getCatalog().getUsedSubTypesFromType(centroidType)
centroidKeys = centroidList[0].keys()
centroidDict = {}

for intID in centroidKeys:
    centroidObj = model.getCatalog().find( intID )
    extID = int(str(centroidObj.getExternalId()))
    centroidDict.update({extID:intID})

sectionType = model.getType( "GKSection" )
sectionList = model.getCatalog().getUsedSubTypesFromType( sectionType )
sectionIDs = sectionList[0].keys()

for sectionID in sectionIDs:
    sectionObj = model.getCatalog().find( sectionID )
    sectionName = str(sectionObj.getName())
    if sectionName[0:10] == "Centroid #":
        numEnd = sectionName.find(",")
        centroidID = int(str(sectionName[10:numEnd]))
        if centroidID > 100:            # leave out microsimulation edge (fake) centroids
            for extID, intID in centroidDict.items():
                if extID == centroidID:
                    centroidObj = model.getCatalog().find(intID)

            origin = sectionObj.getOrigin()
            connector = GKSystem.getSystem().newObject( "GKCenConnection", model )
            if origin is None: # connect from centroid
                connector.setConnectionObject( sectionObj )
                connector.setConnectionType( GKCenConnection.eTo )
            else: # connect to centroid
                connector.setConnectionObject( sectionObj )
                connector.setConnectionType( GKCenConnection.eFrom )

            cenConf = centroidObj.getCentroidConfiguration()
            cenConf.activate()
            centroidObj.addConnection( connector )

print "Done!"
```