ABSTRACT

CLARK, ZACHARY THOMAS. Modeling Impact of and Mitigation Measures for Recurring Freeway Bottlenecks. (Under the direction of Dr. Nagui M. Rouphail.)

Recurrent congestion is a continually growing problem on urban freeways. Facility expansions cannot keep pace with the growing vehicle demand. Low-cost mitigation measures are one way to alleviate the congestion at recurring bottleneck locations. Low-cost measures typically have a life of approximately 10 years and costs ranging from $8,000 to $2.45 million. While benefits have been realized in field applications, only few studies investigated the performance of these measures in terms of added facility capacity.

While micro or macro traffic modeling has long been a tool for planning and analyzing freeway networks, little has been reported regarding model use for estimating the benefits of low-cost freeway improvements. In this study, the author tested proposed treatments at two sites using both a macroscopic and microscopic model. Because empirical performance information of these measures is not available, a purely quantitative analysis would not be feasible since confidence in the values reported would be somewhat low.

Current bottleneck identification methods typically either predict breakdown in real-time or analyze detector data off-line. In order to identify bottlenecks from recorded aggregated data in an off-line simulation model, criteria were generated to identify active bottlenecks and analyze the models' performance in an empirical and qualitative manner.

An assessment of selected available modeling tools is carried out by applying recurring freeway bottleneck criteria to two case study sites where the position and activation times for recurring bottlenecks were known. The sites were modeled under baseline, or non-treated, conditions as well as with the simulated treatments in place. The experience gained

from the modeling exercise enabled the evaluation of the models' ability to simulate the proposed treatments, and the results are used to evaluate the treatment effectiveness on a system-wide basis.

The two most common treatments applied in the case studies are the addition of auxiliary lanes between on and off ramps, and off-ramp facility improvements. Auxiliary lane additions showed reductions of system bottleneck activations in the microsimulation models by 10%, 13%, and 73%. Off-ramp improvements reduced system bottleneck activations in the microsimulation models by 10%, 13% and 32%. In the macrosimulation model, auxiliary lane additions reduced system bottleneck activations by 0%, 33%, and 100% and off-ramp improvements showed a 0% reduction in system bottleneck activations in all instances.

The macrosimulation model proved to be better in identifying hidden bottlenecks and in providing an adequate general overview of the freeway operational quality for the case study locations. The microsimulation model, on the other hand, provided a more realistic representation of the proposed bottleneck treatments and their effects on the entire modeled roadway system. Because of the encountered limitations in both models, a hybrid approach using both model types is recommended

Modeling Impact of and Mitigation Measures for Recurring Freeway Bottlenecks

by

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The author was born in Muncie, IN and attended Yorktown High School in nearby Yorktown, IN. Upon graduation in 1997, he attended Indiana University in Bloomington, IN and graduated in 2001 with a Bachelor of Arts in Physics from the College of Arts and Sciences and a minor from the Kelley School of Business.

After graduating from Indiana University, the author was employed by the Steak ‘n Shake Corporation in various management positions in Bloomington, IN. In 2003, he returned to academia to study Civil Engineering at Purdue University in West Lafayette, IN.

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I. INTRODUCTION

Background

Statistics indicate that congestion delay that is caused by freeway bottlenecks has increased greatly in recent history, and that the top ten freeway bottleneck sites incur approximately 220 million hours of delay per year *(1)*. Bottlenecks have long been characterized as active when vehicles are discharging from an upstream queue unimpeded by conditions downstream *(2, 3)*. Recurring freeway bottlenecks can arise from many conditions which include high mainline or merging demand, lane drops, weaving segments, vertical or horizontal curves, and long inclines.

Freeway bottlenecks have received considerable amount of attention because of their impact on safety, economics, and the environment. Large construction projects typically alleviate bottlenecks but are very costly and require large amounts of time for planning and construction. Smaller scale projects have shown to alleviate at least some, if not all, delay caused by recurring bottlenecks. While these measures may not be as broad or long-lasting, they generally have a high benefit-to-cost ratio *(4, 5)*, increase safety *(4)* and have been shown to reduce driver stress *(6)*.

Literature Review

Ramp metering has, for a long time, been a popular freeway congestion management method in the US, although many other methods are also available to the traffic engineer. Various studies have discussed these other measures *(5, 6, 7, 8)*, but none reported benefits quantitatively in terms of increased capacity or absolute amount of delay reduced.

Additionally, general driver stress reduction has been studied via surveys *(6)* and proposed treatments have been reviewed through judgment though not quantitatively *(7)*.

Machemehl et al discuss general guidelines, advantages, and drawbacks of ramp metering. However this study did not provide quantitative results of real-world implementations. Speed improvements that were observed in a FRESIM analysis are provided in that study *(4)*.

The Institute of Transportation Engineers' (ITE) published toolbox *(8)* does mention increased speeds and volumes, and decreased travel times and average vehicle delay from multiple ramp metering examples. The study does not distinguish between incident and recurrent delay. Reported freeway volume increases ranged from 1.6% to 25%, while speed increases ranged from 16% to 114%. Also reported was an overall average travel time decrease of 16.5% and a site specific travel time savings averaging from 2.5 to 3.5 minutes per vehicle from a metering example in San Francisco, CA at the Oakland-Bay Bridge toll facility. For system-wide applications, freeway congestion was reduced by approximately 60% and speed increases of 30% commonly resulted. It is unclear if this is referring to queue length, delay, or some other measure in the estimation of reduced congestion. Because of the high incident rate at this site (before metering 93% of the morning commute periods had incidents and after 80% had incidents) its effects on recurring bottleneck are difficult to discern. Finally, that study reported that traffic-responsive metering often produces results that are 5% to 10% greater than those that use pre-timed metering. Despite the age of the reported data (from 1980 FHWA report) and its lack of clarity, there are a few items that can be drawn from the study. Since only fixed time meters are to be used in this study, a system-wide treatment can be expected to yield a volume increase in the range of about 2% to 20% and a speed increase on the order of 16% to 30% during the peak analysis period *(8).*

Another study regarding the use of ramp meters in North America *(9)* cites the results of several case studies. Of the studies that performed evaluations, the mainline peak period flows increased 2% to 14.3% due to on-ramp metering *(9)*. However, because in these studies the pre-meter conditions were congested, the metering system essentially restored the freeway to pre-breakdown conditions. As seen in other literature *(2, 10, 11, 12, 13)*, this flow increase is comparable to the difference between pre-queue and queue discharge flows. Therefore, this flow increase is what we would expect, and since most macroscopic models do not recognize a decrease in flow upon queue formation, there is no need to model a capacity increase when modeling on-ramp meters.

The most comprehensive study of low-cost bottleneck solutions was conducted by the Texas Transportation Institute (TTI). Walters et al report 13 low-cost implementations that, over their 10-year project life, yielded benefit-to-cost ratios which ranged from 9:1 to 400:1. Treatments included restriping to add lanes, adding full auxiliary lanes and deceleration lanes, closing and reversing ramps, and widening ramps. Delay hours reduced or capacity increases were not reported. Changes in crash rates, however, were reported. With the exception of two sites, all sites experienced a safety benefit increase ranging from 5 to 76% with an overall average of approximately 35%. Because monetary rates for passenger car and truck vehicle-hour delay, the discount rate, and other assumptions were provided, delay hours reduced could be estimated through back calculation *(5)*.

During the literature review, no single study was identified regarding the modeling of low-cost bottleneck treatments, the ability of models to properly identify bottlenecks, or the expected or observed performance improvements associated with the modeling of low-cost bottleneck treatments.

Context

The study presented in this paper is a portion of the National Cooperative Highway Research Program's (NCHRP) project 3-83, "Low-Cost Improvements for Recurring Freeway Bottlenecks". The objective of the project is to develop a technical guide for identifying existing and future recurring freeway bottlenecks. This technical guide will also provide guidance in determining appropriate low-cost geometric and operational improvements to mitigate the recurring bottlenecks, and to assess the use of analysis tools in identifying, classifying and evaluating the impact of mitigation measures *(14)*. The focus of this research is on the last features in the guide.

A key NCHRP 3-83 project task was to develop an overall framework for bottleneck analysis. This framework is shown in Figure 1. This thesis focuses on the case of existing conditions where real-time data are not available, as indicated in Figure 1 by the heavily outlined text. This portion of the NCHRP study required developing a bottleneck identification process, site modeling and treatment selection, and tool analysis.

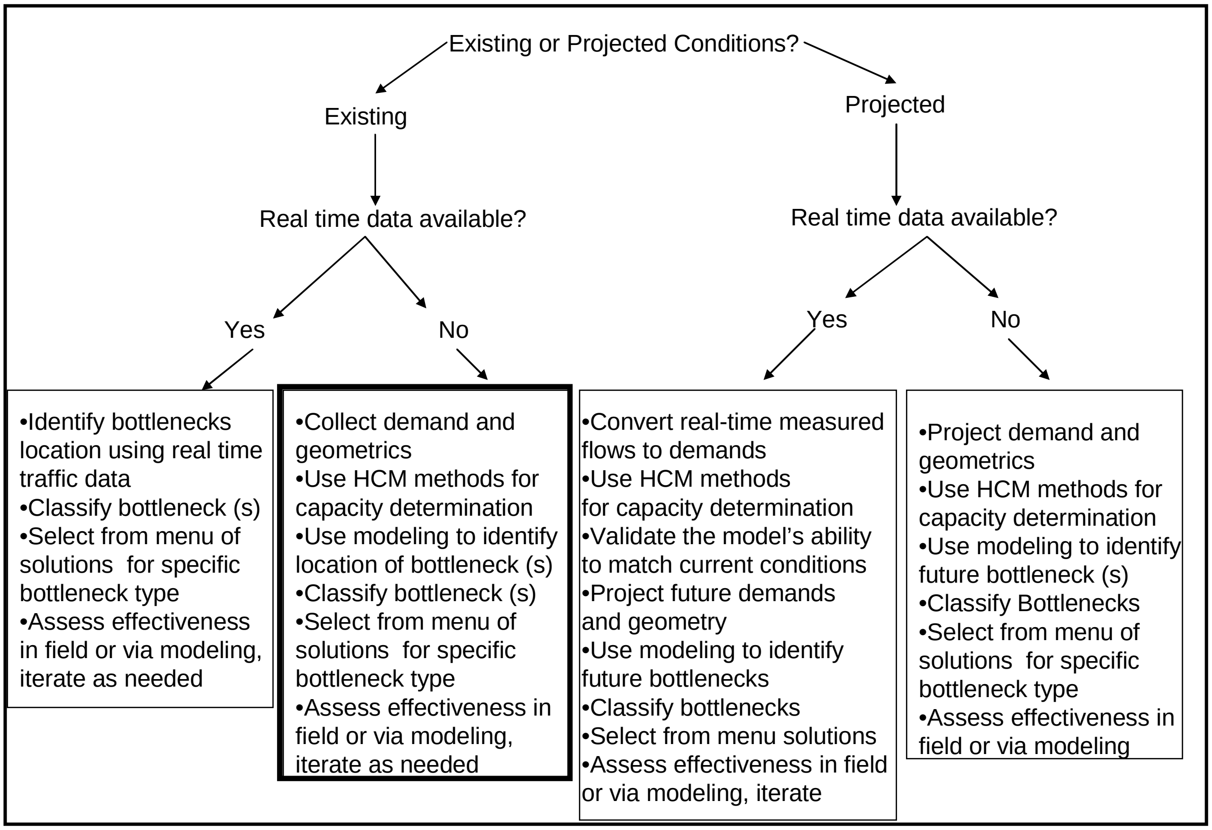


FIGURE 1 Bottleneck analysis framework.

Objective

The objective of the thesis is to assess the abilities of selected modeling tools with respect to (a) identifying recurring freeway bottlenecks (b) to model low-cost bottleneck treatments and (c) how treatments affect the performance of the freeway network. After developing a methodology for identifying recurring freeway bottlenecks in macro and microsimulation environments, bottleneck treatments were modeled and analyzed. Using the modeling experiences and simulation results of the baseline and treated freeway facilities, the modeling tools were analyzed.

As shown in the literature review, modeling tools have been compared and contrasted before, but not with respect to recurring low-cost freeway bottleneck treatments and their ramifications on the performance of the network. Even though empirical performance information was not readily available at recurring bottleneck treatments for comparison purposes, it was nevertheless important to understand how the treatments can be modeled and analyzed using current modeling tools. Through modeling analysis, expected treatment results can be found. Through implemented treatments, field data can be collected and used to develop future models. This is an iterative process that is imperative to the advancement of the engineer’s knowledge with respect to investment returns regarding the implementation of the low-cost measures.

II. ORGANIZATION

This thesis is organized as follows: a methodology for identifying recurring bottlenecks in macro and micro simulation models using a case study approach is first presented (Chapter III). Upon identification, treatments are selected for application based on the suspected causes and the prevailing geometry. After modeling the chosen treatments, their effectiveness is analyzed by applying the recurring bottleneck identification method initially used. Results emerging from one macroscopic and one microscopic simulation models are presented next. An analysis of the modeling tools used is then presented. Conclusions and recommendations for future research are then proposed.

III. METHODOLOGY

The objective of this study was to assess and contrast the impact of recurring freeway bottlenecks using macro and micro simulation tools. The dimensions of the evaluation included bottleneck identification, severity and impact of treatments on traffic performance.

In order to formulate criteria for recurring bottlenecks, a quantitative definition of a bottleneck, its severity and recurrence features need to be developed that are appropriate for application in macro and micro simulation environment. The definition used in this study is based on a set of criteria that were formulated from the literature and engineering judgment supplemented by research associated with NCHRP project 3-83.

After gathering network and traffic data for the case study freeway sites that had known recurrent congestion problems, the proposed definition described in the next section was applied to both a macroscopic and microscopic model. A second objective was also to compare how two different analysis tools would identify and classify the bottlenecks in question.

Replications of the baseline (no improvements) model and the post-improvement models were carried out and the frequencies of bottleneck activations at the identified bottleneck locations and treatment effects were compared.

Recurring Bottleneck Identification

This study deals only with recurring freeway bottlenecks. Bottlenecks caused by adverse conditions, special events, and incidents are outside the scope of the study. Recurrent bottlenecks can be caused by demand exceeding capacity, the physical characteristics of the freeway (e.g. steep upgrades), fluctuations in demand, and traffic operations. For this study, the bottleneck needs to appear at the same location at a regular frequency. Additional details are available in NCHRP 3-83 documents *(14)*

The two selected models do not generate the same outputs from the simulation replications. From the available measures, it is seen that identifying bottlenecks was not particularly difficult.

Common measures are needed to enable comparisons between models. Following the bottleneck activation, the simulation data would generally indicate high densities upstream of the bottleneck, and associated low flows and speeds, while downstream of the bottleneck higher speeds and lower occupancies are expected, unless another bottleneck is active further downstream. Flow density, volume, and speed are measures available in both classes of models. However, thresholds of particular measures should be defined.

It would seem appropriate to associate a vehicle speed reduction of 15-20 mph below the free-flow speed as the speed reduction threshold, but that could vary, depending on the preferences of the state agency. Several studies regarding freeway bottlenecks and congestion considered defining the vehicle speed at a bottleneck. For example, Chen et al defined it as 40 mph on a freeway with a free-flow speed of 60 mph; a difference of 20 mph (*15*). As reported in the NCHRP 3-83 Research Plan Proposal, a congestion map from Caltrans District 3 defined a congested segment as one with average speeds lower than 35 mph for 15 minutes or greater. As this information was also based on freeways in California, a free-flow speed of 60 mph is assumed, providing a speed differential of 25 mph *(16).* Brilon et al also uses a speed threshold set to define breakdown and congestion conditions.

While thresholds are site specific, they were found to be approximately 19-25 mph below FFS *(17)*. Similarly, Gomes et al characterized heavy congestion (speeds under 40 mph), speeds not reaching full congestion (40 – 55 mph), and free flow (speeds exceeding 55 mph) on a freeway based on speed thresholds in their study *(18)*. In the HCM, a speed drop of 5-21.7 mph occurs between free flow and capacity depending on the free-flow speed *(19)*.

A threshold regarding density and/or demand to capacity ratio should be selected as well. The Federal Highway Administration (FHWA) defines “congested” freeway conditions as those with a volume to service flow ratio of 0.8 or greater and “severely congested” conditions with a volume to service flow ratio of 0.95 or greater *(20)*. Bertini and Myton reported a reduction in flow of 3% to 15% upon queue formation. Unfortunately, this study did not include information regarding vehicle speed *(12)*. Cassidy and Bertini reported that the average queue discharge flow rate can be 10% lower than the pre-queue flow rate *(13)*. Bertini *(2)*, Hall and Agyemang-Duah *(11)*, and Banks *(10)* all suggest that the queue discharge capacity is on the order of 10% less than the pre-queue flow.

As mentioned earlier, Caltrans District 3 requires that the freeway segment exhibit low speeds for at least 15 minutes to be considered congested (*15*). The queue features reported by Bertini and Myton reported bottleneck flows ranging in duration from 4 minutes to 22.5 minutes *(21)*. Chen et al defined a bottleneck as sustained if it had at least 25 minutes of active bottleneck activity within 35 consecutive minutes *(14)*. None of these reports required that the bottlenecks be active at any particular weekday frequency.

Since this study’s focus is on recurrent freeway bottlenecks, it is necessary that a minimum active temporal frequency be defined. As part of the study presented by Gomes et al, recurring bottlenecks were identified based on observed data, as opposed to simulation results. Congestion patterns from heavy, typical, and light traffic days as opposed to frequency *(18)*.

In the case of stochastic microsimulation models, if the bottleneck is not activated in a significant proportion of randomly seeded simulation replications, then it is possible that the presence of the bottleneck is merely by chance, because of a confluence of model random number seeds that created a (non-recurring) congested situation. For these reasons a threshold of 50% was chosen. Therefore, if a bottleneck is active during at least 50% of the simulation replications (modeled in the peak periods), it was judged that the frequency is great enough to warrant its designation as a “recurring” bottleneck location. The rationale for not selecting a higher value is that a microsimulation model is likely to not account for all factors that reduce capacity, including driver distraction, geometric effects such as horizontal curves and sight distance constraints, the effects of heavy vehicle on passenger car headways, etc.

In a deterministic macrosimulation model, a facility model is only replicated once. Therefore, a bottleneck activation frequency threshold is not sensible. If one were to be selected it would be 100%. Bottlenecks, hidden or active, will be identified primarily through the demand to capacity ratio (d/c). A d/c greater than 1 will indicate a bottleneck location. Active bottlenecks will be coupled with the appropriate traffic speed reductions, high flows, and queuing where as hidden bottlenecks will not. A hidden bottleneck will produce a d/c >1, however segment speeds and densities will show uncongested conditions.

In summary, and based on a synthesis of the literature review, the following criteria are proposed for identifying recurring bottlenecks in traffic analysis tools.

- Flow downstream of a bottleneck is occurring at a minimum speed that is 85% of the free flow speed.
- Average vehicle speed upstream of the bottleneck is at least 20 mph below the free-flow speed.
- A minimum of 5% segment vehicle flow reduction in queue discharge conditions.
- The three previous criteria sustained for at least one 15-minute analysis period on the same segment.
- The four previous criteria present for at least 50% of the simulation runs.

Based on the model outputs it was possible to evaluate system performance against the proposed criteria. The 3rd criterion is well supported by literature and is a phenomenon that is measurable in this study, even though in the selected models, data were aggregated in 15-minute intervals. Regardless, in models where data are aggregated in intervals greater than 5 minutes, it would seem more appropriate to choose a measure of density as opposed to variations in flow. This is recommended because of the demand fluctuations that can be hidden in data aggregated in longer time periods. Also, since vehicle flow is a function of density and speed, incorporating density in place of flow allows us to equivalently capture the conditions on the freeway. The density threshold used should be one that represents congested conditions and is relatively familiar. For these reasons, a density of threshold of

35 vpmpl, which is the maximum density threshold for a level of service (LOS) D (minimum density threshold for LOS E) as defined by the HCM *(19)*.

IV. ANALYSIS TOOLS

Model Selection

At the onset of this study, three simulation models were selected: FREeway EVALuation (FREEVAL), CORridor SIMulation (CORSIM), and VISSIM as detailed next.

FREEVAL is a macrosimulation model based on the Highway Capacity Manual (HCM). It was developed at North Carolina State University *(22)*. Because the HCM freeway segment procedures do not deal with congested freeway conditions (other than reporting a LOS F), FREEVAL uses a speed-flow curve, shock-wave analysis, and some queuing assumptions to model oversaturation *(23)*. FREEVAL uses the abilities of Microsoft® Excel and Visual Basic programming language to create an uncomplicated macro model of freeway facility operations in a simple spreadsheet format. FREEVAL outputs include segment and facility d/c and v/c, space mean speed, and density contours for undersaturated as well as for congested freeway facilities. FREEVAL reports data for each freeway segment in user defined aggregated time intervals. The data, in conjunction with the speed, density, and volume to capacity graphs generated as part of the output, makes bottleneck identification, both active and hidden, rather straightforward.

CORSIM is a model developed by the Federal Highway Administration (FHWA) that has been in use for several decades by many public and private sector agencies. It contains two microscopic stochastic models; FRESIM and NETSIM. For this study, only the microscopic freeway simulation model component (FRESIM) is considered. CORSIM is a link-node network model where links represent the roadway segments and nodes mark a change in the roadway. CORSIM was developed and is maintained by FHWA. CORSIM is part of the Traffic Software Integrated System (TSIS) that makes use of TSIS's graphical user interface *(24).*

VISSIM was developed at the University of Karlsuhe in Germany in the 1970s (*21*) and was commercially distributed beginning in 1993 by PTV Transworld AG *(25)*. VISSIM is a microscopic simulation model that is time-step and behavioral based. VISSIM incorporates the Wiedemann psycho-physical driver behavior model for the traffic simulator's car following and lane changing logic. The Wiedemann model makes use of the iterative process of deceleration and acceleration used in car following *(26).* VISSIM uses links in the simulator however does not use nodes. This non-traditional structure allows users the ability to control traffic operations and vehicle paths *(25).* VISSIM reports link information, however, due to its microscopic nature will report it in a more detailed manner. Individual vehicle data and the ability to install virtual detectors can provide more precise information on the location of the bottleneck formation. Since FREEVAL lacks this capability, the individual vehicle data feature was not utilized.

As can be seen in the previous paragraphs, even upon selecting models for the study there was quite a difference in the characteristics of the models. It is clear that a comparison of the tools used in this thesis is important and necessary, and will be valuable.

After preliminary modeling efforts with all three models, and discussion among the study team it was decided that only FREEVAL and VISSIM would be further pursued, for several reasons. For one, FHWA support for the CORSIM model is likely to be significantly curtailed in the future. Also, while using CORSIM in the process of compiling the graphically coded model to the text file, not all record types were being included in the text file. Third, access to a freeway facility case study was already available in VISSIM format. Finally, it was felt that a single representative micro simulator would be sufficient to carry out one of the study objectives, namely contrasting different classes of tools. At the end, the two models chosen to be used in this study are FREEVAL Plus and VISSIM 4.10.

FREEVAL is based on the Highway Capacity Manual (HCM). Because this manual is widely used in the US and around the world to evaluate freeway systems, it was important for an HCM-based to be represented among the models chosen. While FREEVAL is not a widely known or utilized macroscopic model, it's ease of use and HCM-based algorithms make it a sensible selection. VISSIM is seeing increased use in the US and abroad for a variety of network analysis problems, and in general is a good representative of modern micro simulation models that practitioners around the country are exposed to. The simulations were replicated on a Dell computer running Microsoft Windows XP Service Pack 2 with an Intel Pentium® 4 3.20GHz processor with 1 GB of RAM.

Model Limitations

Only limitations that pertain to the conduct of this bottleneck identification and analysis study will be discussed in this section. Model limitations outside the scope of this investigation are not reported.

FREEVAL

Because FREEVAL is based on the methods of the HCM, most limitations of FREEVAL are the same as those of HCM freeway facility analysis. These are cited next.

Off-Ramp Capacity FREEVAL does not place a capacity on off-ramps, therefore high off-ramp demands or downstream capacity constraints (such as the presence of a signal) do not propagate congestion on the freeway mainline. This also means that capacity effects of ramp geometry or traffic control at the downstream end of an off-ramp cannot be modeled.

Queue Discharge Rate FREEVAL does not recognize the difference between uninterrupted and queue discharge capacities that has been reported on multiple occasions in the literature *(2, 10, 11, 12, 13)*. While this does not affect queue formation, it does affect the discharge of queues and therefore affects the duration of the queue and the activation and duration of downstream queues. Because of this limitation, the 3rd criterion in the recurring bottleneck definition cannot be met.

On-Ramp Vertical Queuing FREEVAL uses a simple input-output approach to model ramps and assumes vertical queuing on the on-ramps. Queues on an on-ramp that may spillback onto surface streets are not accounted for, although the expected queue length is computed.

Directional Freeway Facilities FREEVAL cannot model a network of freeways; rather it is limited to individual directional freeway facilities, and

Single Calibration Factor Finally, while FREEVAL can model many bottleneck mitigation measures, their effect on capacity must be estimated or calibrated by the user. The only method to do this is through the use in FREEVAL of the Capacity Adjustment Factor that is applied to alter the HCM capacities.

VISSIM

Temporary Lane Closures It was found during the VISSIM coding process that temporary lane closures and or openings (shoulder use during peak; incidents) cannot be directly modeled in VISSIM 4.10. This is a recognized problem *(27, 28)* that is indirectly addressed in VISSIM 4.20. While not mentioned in the VISSIM 4.20 User Manual *(29)* as a way to model temporary lane closures, there is an example of an incident that is provided with the software. The lane closure is created by placing a parking space in the lane that the user desires to be closed, and forcing a vehicle to park in that space at a specified time span. Other methods suggested by PTV (the agent distributing VISSIM), are placing pre-timed signals on the link lane that you wish to open/close or, similar to the aforementioned parking spot example, placing a transit stop at the location of the closure and setting the dwell time equal to the length of the desired closure *(28)*.

The method with the most promise is the *VISSIM Lane-Closure Utility* which was developed by a doctoral student at the University of Minnesota - Twin Cities. This utility allows the user to close multiple lanes on multiple links, customize closure time for each individual lane, and specify prohibited vehicle classes for each individual lane *(27)*.

Unfortunately, while working with the utility, certain flaws were discovered that did not allow it to be used in this project. These issues have been discussed with the developer and updated versions correcting for those flaws are planned to follow.

NEMA Controller Emulator The second set of limitations is that fixed-time signals that utilize the National Electrical Manufacturers Association (NEMA) Emulator in VISSIM do not recognize partial seconds in coding cycle lengths. Preliminary analysis suggests that the algorithm it rounds opposite of standard convention. In other words, it rounds down if the partial second is 0.5 or greater, and up if less than 0.5. For example, a cycle length of 4.3 seconds will act as if it is 5 seconds, and a cycle length of 6.8 seconds will act as if it is 6 seconds. This attribute is not of much concern, other than that fixed-time ramp meters cannot be set as fine. No literature has been found citing this issue for either VISSIM or NEMA controllers.

Shoulder Use While Merging The final limitation of the VISSIM model is that vehicles entering the freeway cannot drive on the shoulder if they are unable to merge in the designated area. The loss in model performance accuracy because of this limitation is most likely negligible. However, the by-product of vehicles being forced to stop at the end of the acceleration lane/taper would seem to have a negative and somewhat unrealistic effect on the capacity of an on-ramp merge.

V. CASE STUDY SITES

Two case studies were performed in this research: this included one site in Milwaukee, Wisconsin and another in St. Louis, Missouri. Both sites are in urban areas and have known recurring freeway bottlenecks.

Milwaukee, Wisconsin

The freeway facility selected at this site is a 9.5 mile section of an urban freeway loop, I-894, in southwest Milwaukee, WI. The study site begins at the I-894/I-94 N-S interchange (Mitchell Interchange) and runs west and then north to the I-894 I/I-94 E-W interchange (Zoo Interchange). Site PM peak traffic data were provided by a consultant of WisDOT and a previous study of the site *(17)*. The provider of the information from Hall et al *(17)* is not known at the time of this draft. Network geometry data were taken from aerial photography. The network and traffic data for this site are from 2003. This is worth noting as changes on the study site have been made since and currently a large nearby freeway interchange (Marquette Interchange) is under construction and is estimated to be affecting the traffic.

The origin-demand matrix of the site is included in the Appendix on pages 85-90. This origin-demand matrix was formulated from a combination of the data from Hall et al *(17)* and the 2003 counts provided by WisDOT. The 2003 traffic counts were first balanced against the two counting stations located within the study site. The origin-demand matrix was then populated through a proportionate distribution. The travel demand information from the Hall et al study was used to determine the fluctuations in traffic demands across the study period.

I-894

The directional freeway modeled is composed of 39 freeway segments, which includes a type C weaving segment, a type A weaving segment, 11 on-ramp merge segments, 2 on-ramp lane add segments, 6 off-ramp diverge segments, and 3 off-ramp lane drop segments. The remaining 15 segments are basic segments. The segments are shown in Figure 2.

Site Traffic Parameters

The free flow speed (FFS) was taken as 60 mph based on the information from Hall et al *(17)*. The desired speed distribution in VISSIM was input as an empirical non-linear distribution from 52.8-74.6 mph. The desired speed distribution was one of the default speed distributions available in VISSIM. Ramp FFS speeds were estimated based on geometry and the ramp speeds at the Missouri study site, which is described later in this chapter.

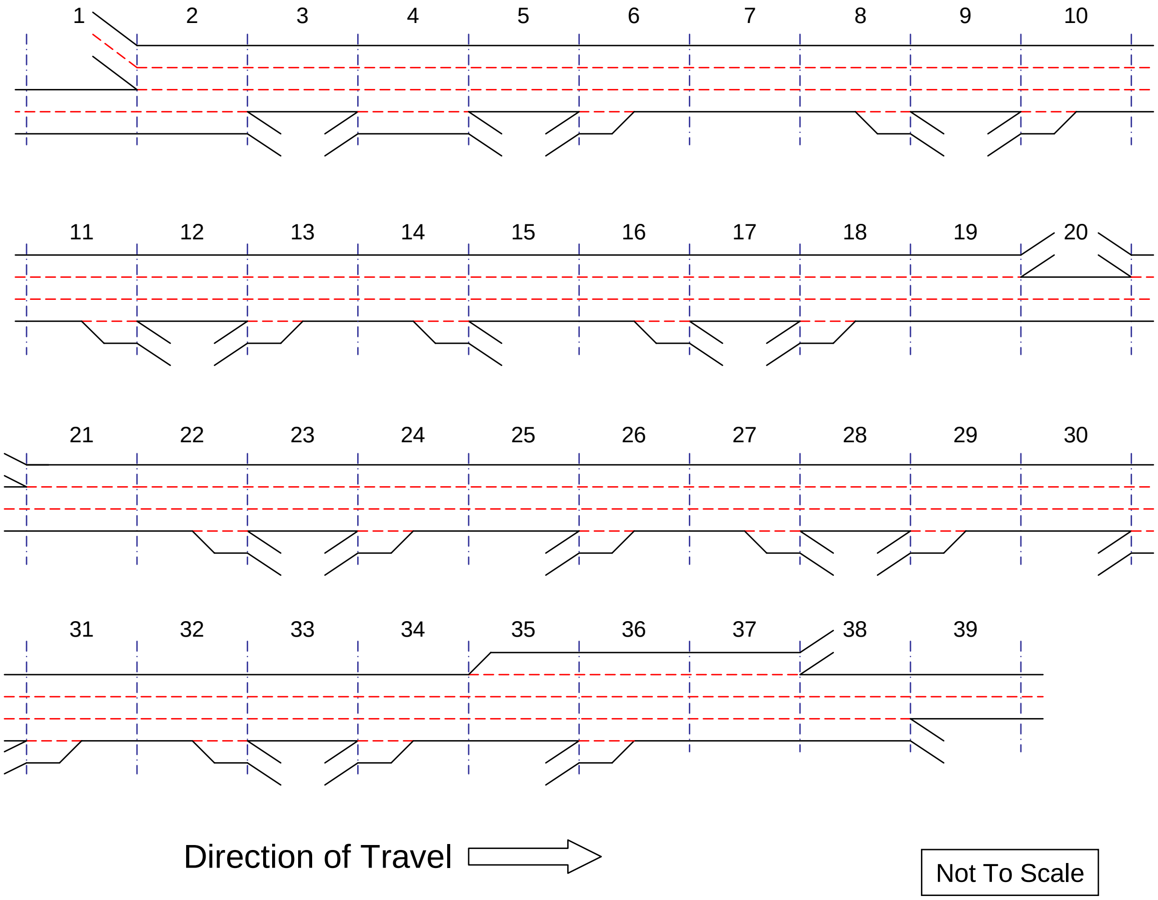


FIGURE 2 Milwaukee, WI case study freeway segments.

Both models were run for twelve 15-minute periods. Periods 4 through 7 represented the peak hour, with a calculated peak hour factor of 0.93.

Because of the lack of detailed speed and volume data at this site, calibration of the model was based on qualitative information gathered from a telephone conversation with a member of WisDOT *(30)*. Default parameters, calibrated parameters from the Missouri (MO) site, and parameters from a site in Pasadena, CA *(18)* were used in VISSIM replications. A combination of parameters reported by Gomes et al for the Pasadena, CA site and from the Missouri provided results consistent with the information from WisDOT. The combination was a result of the MO site non-default parameters focusing on lane changing and the CA site non-default parameters focusing on car following. Additional confidence in the model results can be drawn from the fact that local contacts with individuals familiar with both sites were made. The default parameters, along with the parameters used in the MO site and CA site VISSIM model are located in the Appendix on page 92.

It should be noted that not all of the parameters from Gomes et al were used. Link types in VISSIM were defined as Freeway, SoftCurve, or HardCurve. There were no distinguishing definitions for the SoftCurve and HardCurve link types, and since WisDOT personnel indicated that there was no congestion due to road curvature, only the Freeway link type parameters were used. Also created were Merge link types to accompany each of the 3 previously mentioned types (Freeway, SoftCurve, and HardCurve). The only difference was the "Waiting Time before Diffusion" Parameter *(18)*. This parameter defines the maximum amount of time that a vehicle can wait in the emergency stop position while waiting for a gap to change lanes. Once this time is reached, the vehicle is removed from the network and a message is written to the error file *(29)*. The Merge link types maintained the VISSIM default parameter of 60 seconds, whereas the non-merge link types were set with 1 second. The reason was to eliminate the off-ramp blockages. For the purposes of this study, this seemed inappropriate and unreasonable. This setting would remove any off-ramp spillback that is on the freeway and would therefore not indicate problems in the VISSIM model caused by high off-ramp demand *(18)*. Therefore, only the Freeway link type parameters from Gomes et al were used.

Calibration of the FREEVAL model was done through adjusting segment type capacities to make them representative of the capacities calibrated in the VISSIM model. After the initial capacity adjustment factors (CAFs) were entered, some fine-tuning was necessary to generate queuing at the appropriate locations.

St. Louis, Missouri

The freeway system chosen as the case study is the interchange of I-270 and I-44 southwest of St. Louis, Missouri and the surrounding area. Network and traffic data were provided by the study consultant to the Missouri Department of Transportation. The traffic origin-demand matrix is located in the Appendix on pages 83-84. This included a calibrated VISSIM data set for the site. Figure 3 displays each freeway direction with segment numbers. The freeway segments to be analyzed extend approximately 2.75 miles West and South of the interchange and approximately 2 miles North and East of the interchange. There is a collector-distributor road system along the Western segments of I-44.

I-270 is part of a freeway loop around the city of St. Louis, Missouri. At the location of its intersection with I-44 it is in an orientation of approximately NW-SE. I-44 runs approximately SW-NE. Its Eastern end is in downtown St. Louis and it runs southwest and ends in Wichita Falls, Texas. A diagram of the interchange between I-270 and I-44 is shown below in Figure 4.

Northbound I-270

The Northbound section of I-270 in the study location is approximately 5.58 miles long with 4 mainline lanes. The section is comprised of 14 segments, which includes 3 off-ramp and 3 on-ramp segments. The remaining 8 segments are basic freeway segments. None of the ramp influence area overlap and they appear to be operating independent of each other.

Southbound I-270

The Southbound portion of I-270 in the study location is approximately 5.56 miles long with 4 mainline lanes. The section is made up of 13 segments, which includes 4 off-ramp and 2 on-ramp segments. The remaining segments are basic freeway segments. As with the northbound direction, none of the ramp influence areas overlap.

Eastbound I-44

The Eastbound section of I-44 in the study location is approximately 5.39 miles long with 13 segments. The section begins with 3 mainline lines and increases by one lane (corresponding on-ramp) at the 8th segment. There are two weaving sections; the first is a type B weave on segment 5 and the other is a type A weave on segment 10. Segment 5 also contains a reduced speed area (bridge) that covers a majority of the segment. In addition to the two weaving segments, there are 2 off-ramp segments, 3 on-ramp segments, and 6 basic freeway segments. The influence area of the off-ramp of segment 6 extends approximately 200 feet into segment 5.

Westbound I-44

The Westbound section of I-44 in the study location is approximately 5.45 miles long with 14 segments. The section begins with 4 mainline lanes and decreases by one lane (corresponding off-ramp) at the 4th segment, which is also a type A weaving segment. There is a type C weaving section at segment 4 and a type B weaving section at segment 8. The weaving segments of the Eastbound and Westbound directions run along side each other.

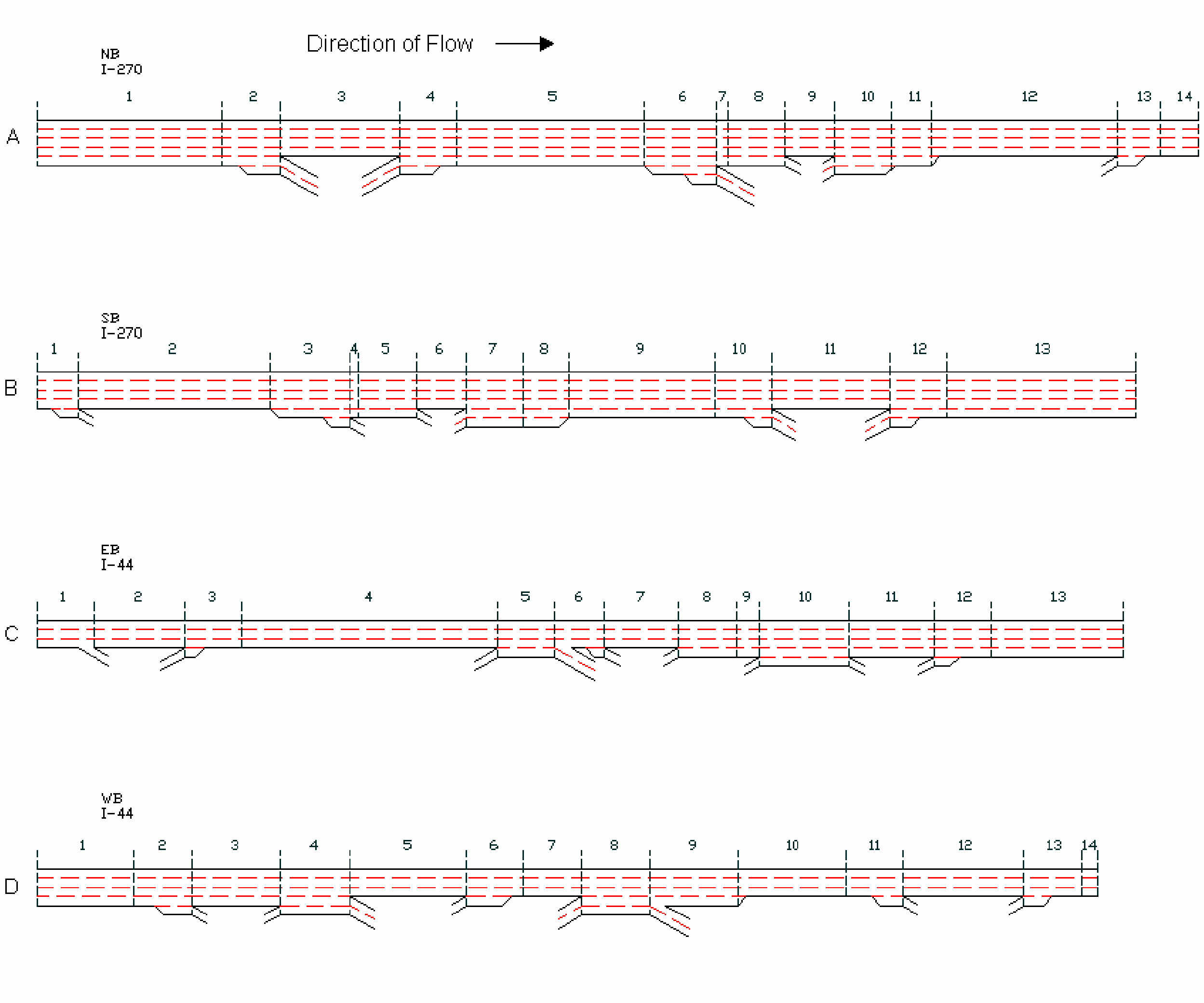


FIGURE 3 Missouri case study freeway segments.

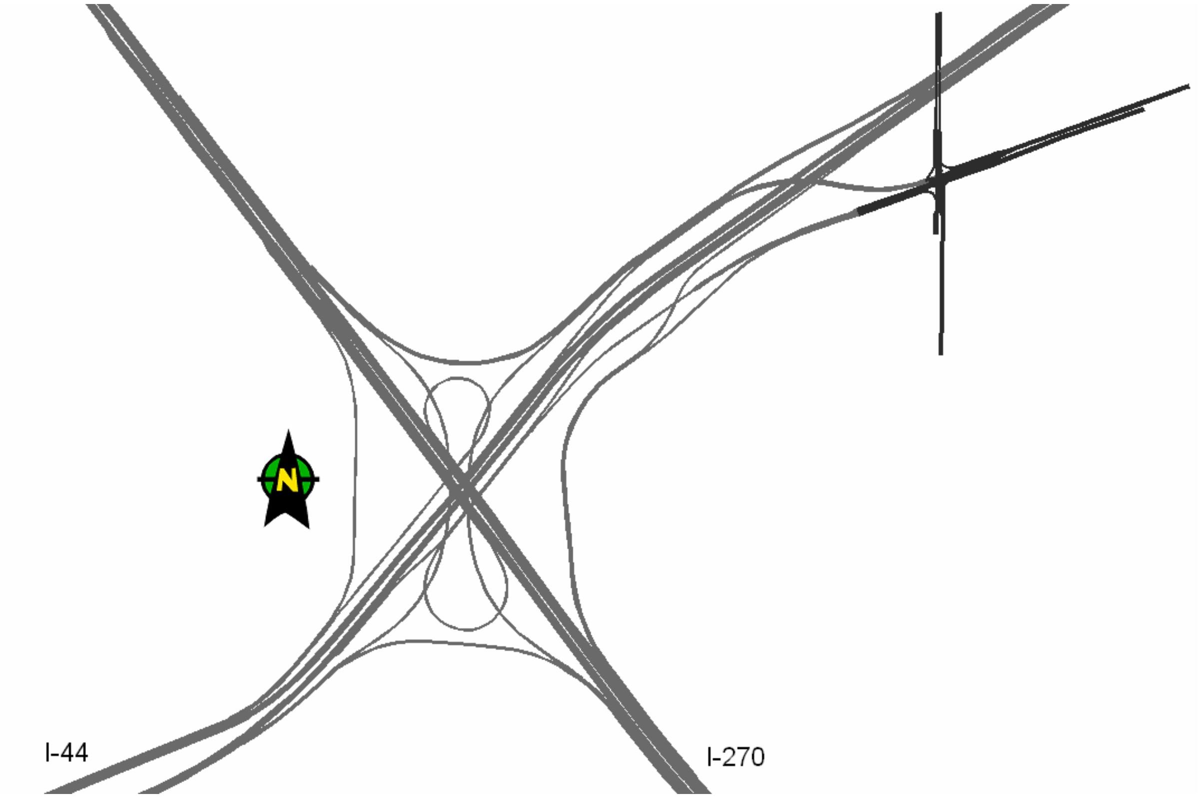


FIGURE 4 Interchange of I-44 and I-270.

Segment 8 also contains a speed reduction area (bridge) that covers a majority of the segment. In addition to the two weaving segments, there are 2 off-ramp segments, 2 on-ramp segments, and 8 basic freeway segments. None of the ramp influence areas overlap and are all independent of each other.

Model Calibration

The VISSIM model of this site was originally modeled and calibrated for the Missouri Department of Transportation (MoDOT) by Crawford, Bunte, Brammeier (CBB). The model was developed and calibrated based on existing geometry, traffic control, link volumes, queue lengths, and travel speeds in 2003 *(31)*.

The existing traffic conditions were based on data collected by CBB and MoDOT. The intersection turning movement volumes were collected by CBB. Existing hourly and historical daily traffic data for I-270 and I-44 and hourly data for all ramp movements were provided by MoDOT *(31)*.

The origin/destination tables were based on traffic counts and weaving observations. These tables were input and modeled as vehicle paths as opposed to turning movement percentages to better reflect actual traffic patterns *(31)*.

Peak hour speed and queue length observations were also performed for model calibration purposes. These were executed using the floating car technique and therefore represent average conditions, and not an 85th percentile speed *(31)*.

The traffic signal timings modeled were based on existing traffic signal timing plans provided by MoDOT *(31)*.

The existing conditions were calibrated so that the modeled volumes on all segments generally fell within 5% or 50 vehicles of actual field volumes. The parameters of the model were adjusted so that the queue lengths and travel speeds reasonably replicated field conditions. The calibration measures were based on an average of only five random replications of the models *(31)*.

While the model may have generated the existing conditions, there were two concerns regarding the original model. The first concern is that the model was only replicated five times. First, the simulation literature recommends that a minimum of 10 replications for stochastic models be carried out *(18, 21, 32)*. The other concern was not apparent until the VISSIM model was replicated and the animations were viewed. At congested on-ramp merge locations, instead of ramp merging and mainline traffic taking turns creating a zipper-like weave, the merging vehicles would be stopped on the acceleration lane waiting for an acceptable gap. This is not what one would expect to observe in the field. In addition to the non-realistic vehicle behavior, this process also caused vehicles to be dropped from the network if they had stayed in the stop position for 60 consecutive seconds.

Site Traffic Parameters

The desired / FFS speed in VISSIM was expressed as a distribution with a median value of 62.3 mph while FREEVAL only allows the input of a single free-flow speed (FFS). This was accounted for, by taking the 50th percentile speed value from the distribution curve in the VISSIM model. This was done for the mainline FFS as well as for the ramp FFS's. Otherwise, all FREEVAL model default parameters were kept in the baseline runs.

Both models were run for eight 15-minute periods. The first and last two periods were intended to model the shoulder (increase and decrease) demand periods. The third through the sixth periods used vehicle demands representative of the AM peak.

There was only one recurring bottleneck that was communicated to the author based on local site observations, and that bottleneck was determined to be located at the last on-ramp on Northbound I-270 (segment 13 in Figure 3a).

Model Replications

For this study, the VISSIM models were replicated 10 times and the FREEVAL models once. Ten replications were made for each scenario in the VISSIM model, to account for the stochasticity in the model results. The number of replications was based on recommendations in the literature *(18, 21, 32)* and engineering judgment. The rationale for the single run in FREEVAL is that it is a macro simulation deterministic model, and therefore results will not vary between replications.

VI. SENSITIVITY ANALYSIS

In order to the test the sensitivity of the simulation software and the previously defined recurring bottleneck definition, a sensitivity analysis was performed. Origin-destination demands were adjusted to 90, 110, and 120 per cent of the baseline conditions in order to test the sensitivity of the models as well as the previously defined bottleneck criteria. A sensitivity analysis was conducted only at the Missouri site since there was greater confidence in the level of accuracy in the model calibration at that site.

Simulations

As with the baseline model, each of the adjusted traffic volume models were replicated 10 times with different random number seeds in VISSIM. Because FREEVAL is a macroscopic model, it was only simulated once per traffic volume adjustment. Five different bottlenecks appeared during the simulations. These are discussed in the following paragraphs.

Northbound I-270 Segment 13 (ONR)

This bottleneck is caused by a combination of high mainline traffic volumes and the demand of the traffic entering the freeway from Big Bend Rd. as shown in Figure 3A. The traffic merging from the on-ramp is not metered and there is not a traffic signal at the top of the on-ramp at Big Bend Rd so there is nothing currently in place to regulate the traffic entering the freeway.

As show in Table 1, even when the traffic volumes are reduced to 90% of the baseline volumes, the bottleneck is activated in 9 of the 10 replications. However, FREEVAL does not predict a bottleneck when the traffic volumes are reduced. The bottleneck is produced in all of the baseline replications, and as would be expected the replications with increased traffic demands.

Table 1: Northbound I-270 Segment 13 (ONR)

Traffic Volume Level	FREEVAL	VISSIM
90 %	0/1	9/10
Baseline (100%)	1/1	10/10
110%	1/1	10/10
120%	1/1	10/10

Northbound I-270 Segments 10-11 (ONR+LD)

This bottleneck is a combination of the lane drop in Segment 11 and the merging traffic from the on-ramp in Segment 10 as shown in Figure 3A. The on-ramp in Segment 10 is a 2-lane ramp with 2 acceleration lanes. Because the 2nd acceleration lane doesn't drop within 1,500 feet of the on-ramp gore, it is treated as an on-ramp segment followed by a lane-drop segment. The two segments cover a distance of approximately 2,500 feet. This is a potential interactive bottleneck, which is often exacerbated by the downstream queuing of vehicles at the above described bottleneck at Segment 13. This likely interactivity is most likely the cause for the high sensitivity to traffic volume, demonstrated by the drastic difference in bottleneck occurrences in Table 2. It should be noted that because of the queuing from the bottleneck at Segment 13, this bottleneck cannot meet criterion 1.

Table 2: Northbound I-270 Segment 10-11 (ONR+LD)

Traffic Volume Level	FREEVAL	VISSIM
90 %	0/1	0/10
Baseline (100%)	0/1*	10/10
110%	1/1	10/10
120%	1/1	10/10

**FREEVAL places the queue on the on-ramp because of a downstream queue and therefore a bottleneck doesn't show up on the mainline.*

Southbound I-270 Segment 3 (OFR)

Congestion at this segment is actually a byproduct of the bottleneck at the downstream off-ramp in segment 5, as shown in Figure 3B. The segment 5 off-ramp, a tight loop ramp, occurs in conjunction with a lane-drop. The exiting demand exceeds the capacity of the ramp and slowing and spillback is created on the right lane of the freeway. Also, because of the fairly close proximity of the ramps (~1,800'), vehicles desiring to exit at the downstream ramp, are often in the far right lane before the upstream ramp diverge. These vehicles reduce the available capacity of the lane and vehicles wishing to exit at the upstream ramp have a difficult time reaching the ramp if they have not moved into the right lane well upstream. When the queuing of the downstream ramp extends upstream to segment 3, it creates congestion and triggers bottleneck identification when using the pre-defined criteria. While delay on segment 5 occurs in all baseline VISSIM replications, it only creates active bottleneck conditions at segment 3 in half of the baseline replications, as shown in Table 3. The reason that the bottleneck and subsequent congestion are never predicted in FREEVAL is because of its inability to handle lane-by-lane analysis. This phenomenon will be revisited and used in adjusting the bottleneck criteria.

Table 3: Southbound I-270 Segment 3 (OFR)

Traffic Volume Level	FREEVAL	VISSIM
90 %	0/1	0/10
Baseline (100%)	0/1	5/10
110%	0/1	10/10
120%	0/1	10/10

Eastbound I-44 Segment 5 (WB)

This congested location is a type B weave along with a speed reduction zone and a narrowing of lanes, as shown in segment 5 of Figure 3B. A majority of the segment is on a bridge deck. While this segment's demand does not reach or exceed the capacity as calculated by the HCM, it does have a high weaving volume (>2,000 vphpl), a moderate volume ratio ($v_w/V = 0.34$), and a moderate weaving ratio (v_{w2}/v_w). The volume ratio is not exceptionally high; however, type B weaving configurations are usually more sensitive to the volume ratio since non-weaving vehicles are more likely to share lanes with weaving vehicles than in a type A configuration *(19)*.

As can be seen in Table 4 below, VISSIM predicts a bottleneck in 7/10 of the replications with baseline traffic volumes and all of the replications for both the increased traffic volume configurations. FREEVAL only predicts active bottleneck conditions when the traffic volumes are increased to 120% of the baseline conditions.

Table 4: Eastbound I-44 Segment 5 (WB)

Traffic Volume Level	FREEVAL	VISSIM
90 %	0/1	0/10
Baseline (100%)	0/1	7/10
110%	0/1	10/10
120%	1/1	10/10

Westbound I-44 Segment 4 (WC)

This section is a type C weaving segment over 2,300’ in length. This weave is shown in segment 4 of Figure 3D. As can be seen in Table 5, active bottleneck conditions are only predicted when volume is increased, and not during the baseline replications. Because a bottleneck does not occur under baseline conditions, treatments will not be modeled at this segment.

Table 5: Westbound I-44 Segment 4 (WC)

Traffic Volume Level	FREEVAL	VISSIM
90 %	0/1	0/10
Baseline (100%)	0/1	0/10
110%	0/1	3/10
120%	0/1	6/10

Summary

The sensitivity analysis described in this chapter has shown that VISSIM is not highly sensitive to low to moderate changes in traffic volumes. Incremental increases in traffic volume did not create large sways in the frequency of bottleneck activations in the model. This characteristic is reassuring for the modeling of bottleneck treatments. Because of the model’s moderate sensitivity, drastic and unrealistic changes in the network performance are not expected with the introduction of treatments.

The sensitivity analysis results do not seem to reveal much about the FREEVAL model. The segment with the known bottleneck, NB I-270 segment 13, no longer activates a bottleneck when the volume is reduced. However, at the three sites that do not show congestion under baseline conditions, SB I-270 segment 3, EB I-44 segment 5, and WB I-44 segment 4, when traffic was added, only one of the segments predicted an active bottleneck. Based on the results, it does not seem that the model is extremely sensitive. But, with a deterministic model such as FREEVAL, sensitivity can be difficult to gauge.

VII. TREATMENT MODELING METHODS AND RESULTS

Combinations of five types of treatments are modeled and evaluated in the two case studies

- Simple fixed-time ramp metering
- Off-ramp widening
- Auxiliary lane construction
- Restriping and lane-narrowing in conjunction with plus-lane
- Restriping without narrowing lanes.

Ramp Metering

Ramp metering was modeled in VISSIM and FREEVAL using a simple fixed-time strategy that was implemented during the peak period and the following 15-minute period. The capacity of the meter was set to allow the queue created to dissipate before the meter was turned off as well as not spill back onto the surface streets. Meters were located in order to allow appropriate acceleration distance as outlined by the American Association of State Highway and Transportation Officials (AASHTO) Green Book *(33)*. In some instances, where storage was small or the metering was set to favor the freeway, trucks were not required to stop at the meter in the VISSIM model.

In some instances, in the VISSIM model, as opposed to metering with a traditional traffic signal, a speed reduction zone was created on the on-ramp in order to create the appropriate amount of vehicle delay.

Off-Ramp Widening

In the two instances where off-ramps were widened at the Missouri site, the freeway lanes were converted from a single exiting deceleration lane, to an exiting deceleration lane and a through-exit lane. At the Wisconsin site, the widening was of a freeway-to-freeway ramp which the upstream portion was a freeway split. Instead of 3 lanes splitting to 2 lanes and 1 lane, the 3 lanes split to two 2-lane facilities.

Auxiliary Lane Construction

Auxiliary lane construction was completed by simply adding a full 12-foot lane on the right side of the freeway.

Lane Narrowing and Plus-Lane Addition

A plus-lane is a travel lane that is added on the median side of the freeway ONLY during heavy demand periods. Because it essentially opens the left shoulder for travel, the lane is narrower than a standard travel lane and is closed to heavy vehicles (trucks). Because the lane is relatively narrow, it is not expected to add the capacity of an entire lane on this section. Plus lanes have been used in the Netherlands successfully for a number of years. Figure 3 illustrates the concept of the lane use during peak (low speed, 70 kph or 42 mph) and off peak (high speed 100 kph, or 63 mph) periods. Of course, such a system would require lane control signals as indicated in Figure 5. Camera enforcement is used to insure compliance with the lane use in the off peak periods.

FIGURE 5a Plus lane closed during off-peak period.

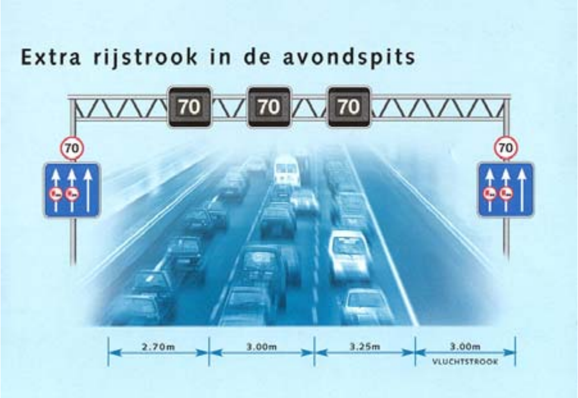


FIGURE 5b Plus lane open during peak period.

Restriping was completed by narrowing lanes so that there was room for an additional left-side lane on the existing pavement. Lane restrictions in the VISSIM model kept the trucks from the more narrow left lanes. Reduced speed zones were also created to simulate the expected speed reduction and capacity reduction created by the more narrow lanes. Speeds were reduced in accordance with the HCM lane width adjustment factor for calculating FFS *(19)*.

While there are no examples of this in the United States, through public education, it could become viable option.

Restriping Without Lane Narrowing

This treatment was possible in locations where ample paved shoulder was available to add a full 12 foot lane through restriping. It is assumed that the shoulders in these locations are full-depth pavement.

Results Under Baseline Conditions

Using the aforementioned outlined bottleneck criteria, multiple bottlenecks were identified in the models under baseline conditions.

Model Bottlenecks – Wisconsin Site

Segment 1 (Basic) In 1 of the 10 VISSIM replications, bottleneck conditions occur at this location. This segment is essentially a 2-lane freeway connector. The activation appears to be a by-product of a slight slow-down immediately downstream in segment 2, which is a type C weave. Congestion is not predicted in the FREEVAL model, nor is a hidden bottleneck predicted.

While this location does not meet the criteria for a recurring bottleneck, the location will be specially noted since there was an activation in the baseline conditions.

Segment 4 (Type A Weave – 27th St. Interchange) A bottleneck is activated in 7 of 10 VISSIM replications at this segment. The length of the weave is short at 320 feet, exacerbating the situation as neither of the demands for the ramps are high. A bottleneck was predicted in the FREEVAL model.

Segment 6 (On-Ramp Merge – 27th St. Interchange) This segment is predicted to be a hidden bottleneck in the FREEVAL model. There is no indication in the VISSIM model results that this segment will is a potential hidden bottleneck.

Segment 10 (On-Ramp Merge – Loomis Rd. Interchange) Bottleneck conditions are predicted at this segment in all 10 of the VISSIM replications. The congestion is a result of significant mainline demand and a short taper type on-ramp (approximately 200 feet). The FREEVAL model predicted a bottleneck at this location.

Segment 13 (On-Ramp Merge – 60th St. Interchange) This location does not qualify as a recurring bottleneck by the criteria earlier set forth; however, it does show as a bottleneck in 1 of the 10 VISSIM replications. Because of this section's location, it creates somewhat of a dilemma. Using the calculated CAF for an on-ramp merge location does not create a hidden bottleneck in FREEVAL, although one would suspect one at this location given the VISSIM results.

The baseline maximum demand to capacity ratio at this location is 0.986 with a corresponding volume to capacity ratio of 0.973, meaning that a hidden bottleneck could be created at this location by reducing the CAF. But since we do not know if the segment is a hidden bottleneck from field verification, it would be irresponsible to force a hidden bottleneck. To remain within the spirit of the study, acting with a lack foresight, a hidden bottleneck will not be forced in FREEVAL at this segment.

Segment 18-19 (Non-HCM Weave – Hale Interchange) This 3000 foot section is a right-side on-ramp merge followed by a left-side off-ramp lane drop, as shown in Figure 6. The bottleneck is caused by a combination of high off-ramp demand (approximately 2,000 vph) and the weaving vehicles. This bottleneck was active in 9 of 10 VISSIM replications and was predicted in the FREEVAL model. Because the distance between ramps is 3,000 feet, it is divided into an on-ramp and off-ramp segment as per HCM standards *(19)*.

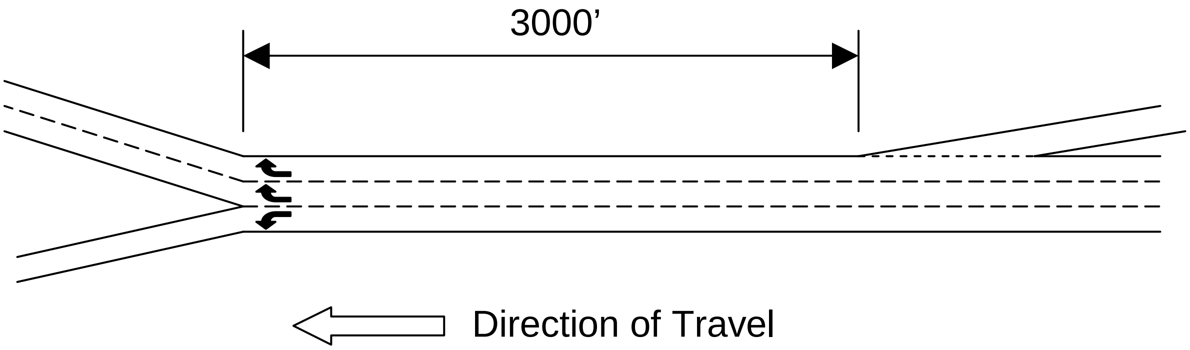


FIGURE 6 I-894 Segment 18-19 Weaving Section

Segment 31 (On-Ramp Merge – Lincoln Ave Interchange) This bottleneck is simply created by the merging and mainline demand exceeding the capacity.

This bottleneck was predicted in 7 of 10 VISSIM replications.

In the FREEVAL model, a maximum d/c ratio is predicted above 1, however, the maximum v/c ratio is predicted to be 0.981 and therefore no queue is predicted. The FREEVAL model does predict a decreased traffic speed (47 mph) and relatively high density (41 vpmpl) at the segment. By FHWA standards, this segment would be considered “severely congested” *(6)*. Both models, while not necessarily producing similar results, do seem to represent the conditions of the segment as expressed by WisDOT *(30)*.

Segment 34 (On-Ramp Merge – EB Greenfield Ave Interchange) This bottleneck was predicted in 5 of 10 VISSIM replications. Similar to the bottleneck upstream at segment 31, the queuing is created by the demand of the mainline and on-ramp merge is greater than the capacity.

In the FREEVAL model, a maximum d/c ratio is predicted above 1, however, the maximum v/c ratio is predicted to be 0.994 and therefore no queue is predicted. The FREEVAL model does predict a decreased traffic speed (44 mph) and relatively high density (42 vpmpl) at the segment. By FHWA standards, this segment would be considered “severely congested” *(6)*. Both models, while not necessarily producing similar results, do seem to represent the conditions of the segment as expressed by WisDOT *(30)*.

Model Bottlenecks – Missouri Site

Northbound I-270 Segment 13 (On-Ramp Merge) This was the original bottleneck communicated by the agency to the author. The bottleneck at this location is caused by the demand from the merging traffic and the mainline traffic exceeding the capacity of the downstream freeway segment. This bottleneck was active in all 10 of the VISSIM replications and in the FREEVAL model. Figure 7a shows the speed profiles from the 2 models at this location. As can be seen in the plot, the bottleneck activations occur at approximately the same time in the simulations. In FREEVAL, and 9 of 10 of the VISSIM replications, the bottleneck becomes active in time period 3. The bottleneck becomes active in 1 of 10 of the VISSIM replications in time period 4. The activation time appears to be longer in VISSIM than in FREEVAL by about one time period (15 minutes).

Northbound I-270 Segments 10 (On-Ramp Merge) Although this site does not satisfy all of the defined recurring bottleneck criteria, it will be treated as a potential bottleneck that is hidden by queuing downstream of the section. The rationale here is that the speeds during congestion are lower on segment 10 than they are downstream at segment 13, which is defined as a recurring bottleneck. This can be seen when comparing the speed profiles of the two segments, as seen in Figures 7a and 7b.

This potential bottleneck is similar to that of segment 13's in that it is possibly caused by high on-ramp and mainline demand. The on-ramp is a two-lane freeway-to-freeway ramp. The congestion is fueled by queuing at downstream segment 13 described above. The congestion is present in all VISSIM replications and the FREEVAL model. Figure 7b shows the speed profiles of the 2 models at this location.

Eastbound I-44 Segment 5 (Type B Weave) The bottleneck at this location is caused by congestion on the off-ramp of the weave. The off-ramp feeds into the on-ramp at segment 10 of NB I-270, which is discussed above. The bottleneck does not appear in FREEVAL because of its limitations in modeling networks and off-ramp capacity, but is active in 7 of 10 VISSIM model replications. Therefore, it qualifies as a recurring bottleneck in the VISSIM model by our defined criteria. The bottleneck does not always activate in the same time period in the VISSIM model. Figure 7c shows the speed profile of this segment.

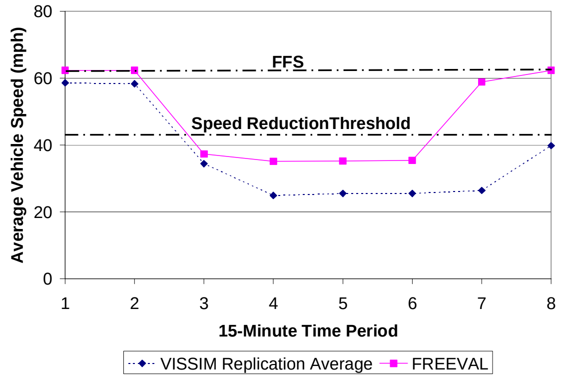


FIGURE 7a Northbound I-270 Segment 13 (On-Ramp Merge) speed profile.

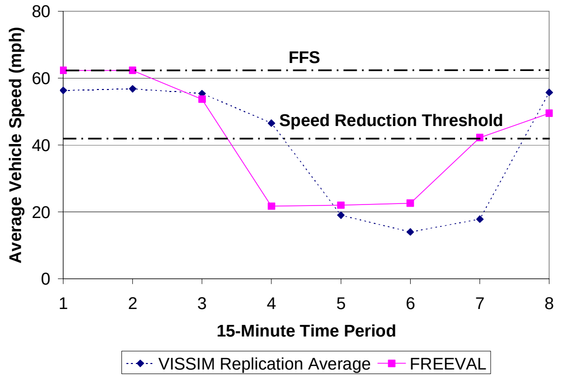


FIGURE 7b Northbound I-270 Segment 10 (On-Ramp Merge) speed profile.

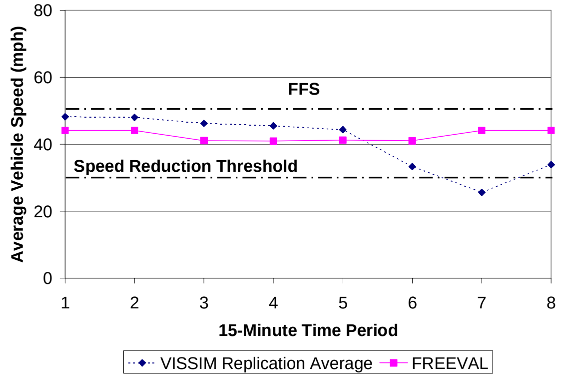


FIGURE 7c Eastbound I-44 Segment 5 (Type B Weave) speed profile.

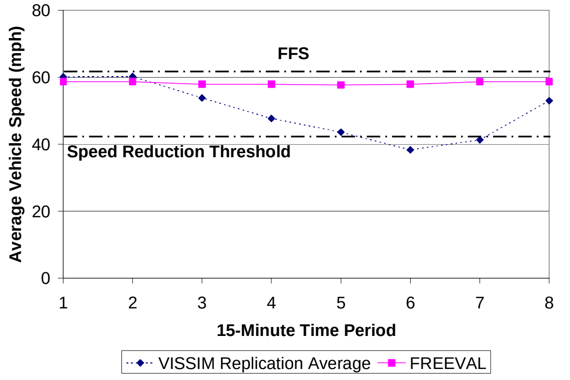


FIGURE 7d Southbound I-270 Segment 3 (Off-Ramp Diverge) speed profile.

Southbound I-270 Segment 3 (Off-Ramp Diverge) The recurring bottleneck at this location is caused by high off-ramp demand that creates spillback onto the freeway. The bottleneck is active in 5 of 10 of the VISSIM replications. The bottleneck does not activate during the same time period every time. The bottleneck is not predicted in the FREEVAL in the model. It is not activated in the FREEVAL model because FREEVAL does not recognize off-ramp capacity, as mentioned in the model limitations.

Congestion at this segment was thought to be exacerbated and possible caused by queuing in the right lane for the downstream off-ramp lane drop at segment 5. Therefore, treatments are modeled at both segment 3 and 5 on Southbound I-270. Figure 7d shows the speed profiles of the 2 models at this segment.

Confirmed Findings The only confirmed bottleneck reported to the research team was on Northbound I-270 segment 13 (Figure 7a). Both FREEVAL and VISSIM predicted bottleneck activations at this location. FREEVAL did not predict bottleneck activations at any other location, whereas VISSIM predicted two other bottleneck location on Southbound I-270 segment 3 (Figure 7b) and Eastbound I-44 segment 5 (Figure 7c). Congestion was reported to us on EB I-44 segment 5 by the modeler but not on SB I-270 segment 3.

The FREEVAL and VISSIM models did not produce the same results regarding bottleneck conditions on the network. This is caused by limitations of the models; most notably the inability for FREEVAL to explicitly model multiple freeway facility interactions and that FREEVAL does not recognize off-ramps as having capacity constraints.

Discussions with the modeler of the VISSIM network confirmed congested conditions at the two Northbound I-270 locations (segments 13 and 10) and the Eastbound I-44 location (segment 5), but not on segment 3 of Southbound I-270. The assertion is that Segment 13 of Northbound I-270 was the only true bottleneck and that the congestion upstream at Segment 10 of Northbound I-270 and at segment 5 of Eastbound I-44 were caused by queues extending upstream on the through lanes as well as the ramp connecting the two freeways.

Results Under Bottleneck Treatment Conditions

Wisconsin Site

Segment 1 (Basic) No treatments were modeled to specifically target this location. However treatments that were performed at segment 4 did have an effect on this location in the VISSIM model. This is discussed in the following paragraphs.

Segment 4 (Type A Weave – 27th St. Interchange) The baseline conditions of the I-894 interchange with 27th St. can be seen below in Figure 8a. As shown, it is currently a short type A weave. Two treatments were applied at this location.

The first, shown in Figure 8b, is converting the weave to a type B by extending the auxiliary lane, through restriping, past the off-ramp. This was completed in both VISSIM and FREEVAL by adding a lane on the right in order to create 4 lanes in the basic segment immediately downstream of the weaving segment. In order to model the end of the auxiliary lane before the following on-ramp merge, an additional 3-lane segment was inserted.

The second treatment, shown in Figure 8c, is the treatment that has been applied by WisDOT at this location. The treatment involved physically removing the off-ramp of the weave, straightening the downstream on-ramp, lengthening the auxiliary lane through restriping, and signalizing the surface street intersection. WisDOT did place ramp meters on both of the on-ramps, however those were not modeled in this treatment. This treatment seems to be a more expensive and permanent solution than that shown in Figure 8b.

Both of these treatments removed the bottleneck activations in this segment in both the FREEVAL and VISSIM models. In the FREEVAL model, queuing was predicted immediately downstream at the second on-ramp of the interchange (segment 6). The capacity adjustment factors were not adjusted between treatments. VISSIM did not predict this occurrence.

However VISSIM did predict changes in the bottleneck activations throughout the network, in addition to the one remedied at this location. The changes to the downstream bottlenecks can be mostly attributed to the change in the traffic pattern as well as the increase in arriving demand. One would think that the bottleneck at segment 10 would still meter the downstream traffic and therefore the performance of downstream segments should not be affected, however, the increase in severity (length and duration) of the queuing at this location would create changes in the downstream flows, and therefore the bottleneck activations. The changes in the VISSIM model performance in the upstream congestion in segment 1, is most likely an outcome of the stochasticity of the model as well as the removal of slower traffic downstream.

Segment 6 (On Ramp Merge – 27th St. Interchange) No treatments were modeled to specifically target this location. As discussed in the previous paragraphs, treatments that were performed at segment 4 did have an effect on this location in the FREEVAL model.

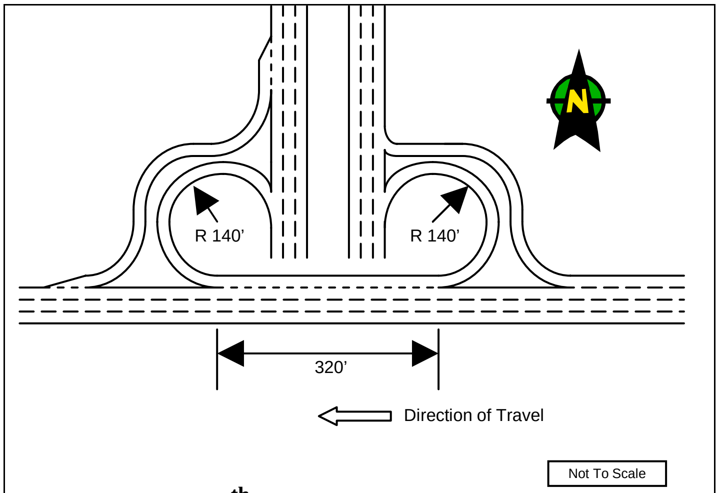


FIGURE 8a 27th St. interchange baseline conditions.

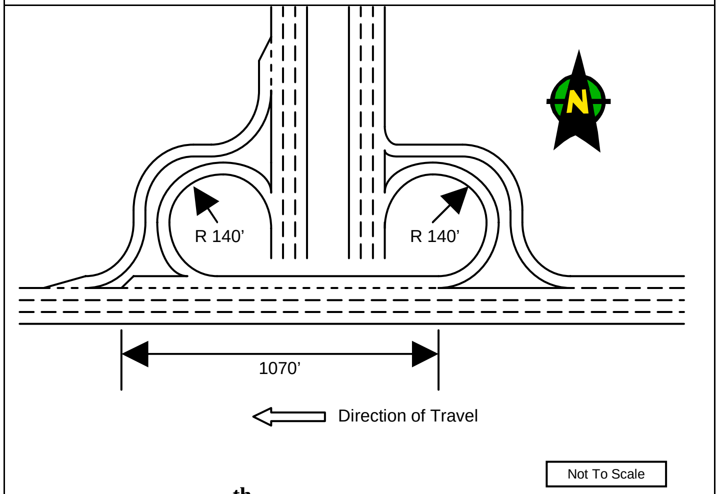


FIGURE 8b 27th St. interchange type B weave.

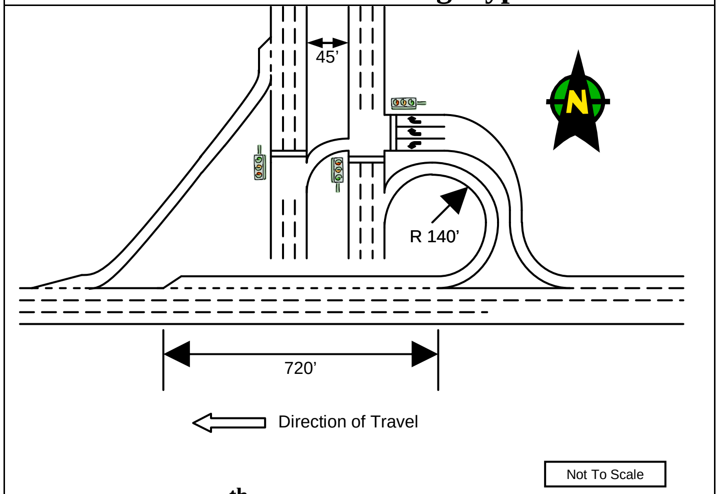


FIGURE 8c 27th St. interchange ramp closure.

Segment 10 (On-Ramp Merge – Loomis Rd. Interchange) The treatment that was applied to this bottleneck location was the addition of an auxiliary lane between the Loomis Rd. on-ramp to the downstream off-ramp at 60th St. The distance between the two ramps is approximately 2500' gore to gore, and would therefore create a type A weave as per HCM definitions *(19)*. This lane addition would be possible through restriping as both the left and right shoulder are approximately 11 feet wide.

The treatment removed the bottleneck activation in all VISSIM replications and in the FREEVAL model. In the VISSIM model, a recurring bottleneck was created at the downstream on-ramp at 60th St. A bottleneck was active in 6 of 10 replications at the 60th St. on-ramp merge. This bottleneck was not predicted in the FREEVAL model.

In VISSIM this treatment was modeled by adding a lane to the links between the merge and diverge links and connecting them appropriately. In FREEVAL, because the auxiliary lane created a type A weave, the section was changed from an on-ramp merge segment and off-ramp diverge segment to one type A weave segment.

Segment 13 (On-Ramp Merge – 60th Street) As mentioned earlier, this segment experienced an active bottleneck in 1 out of 10 VISSIM replications and no bottleneck was predicted in the FREEVAL model, and therefore is not a recurring bottleneck. However, a bottleneck does appear in 6 out of the 10 VISSIM replications when the previously described treatment is applied to the Loomis Rd on-ramp merge bottleneck.

No treatment was applied specifically targeting this segment.

Segments 18-19 (Hale Interchange – Non-HCM Weave) The baseline condition of this section is shown in the top diagram of Figure 9. As can be seen, vehicles that are entering via the on-ramp and wish to exit via the left branch are forced to merge 3 times including the initial merge from the ramp to the mainline. This, in conjunction with the high demand for the left exiting branch, causes a capacity reduction and subsequent bottleneck.

The treatment applied involves widening the exiting left-branch to two-lanes as shown in the bottom diagram of Figure 9. This reduces the number of necessary merges and increases the capacity of the ramp. However, this treatment would require widening the pavement, a bridge deck, and possibly require construction on a bridge overpass and would therefore be a relatively more costly and a long-term solution. The placement of the bridges can be seen in Figure 10.

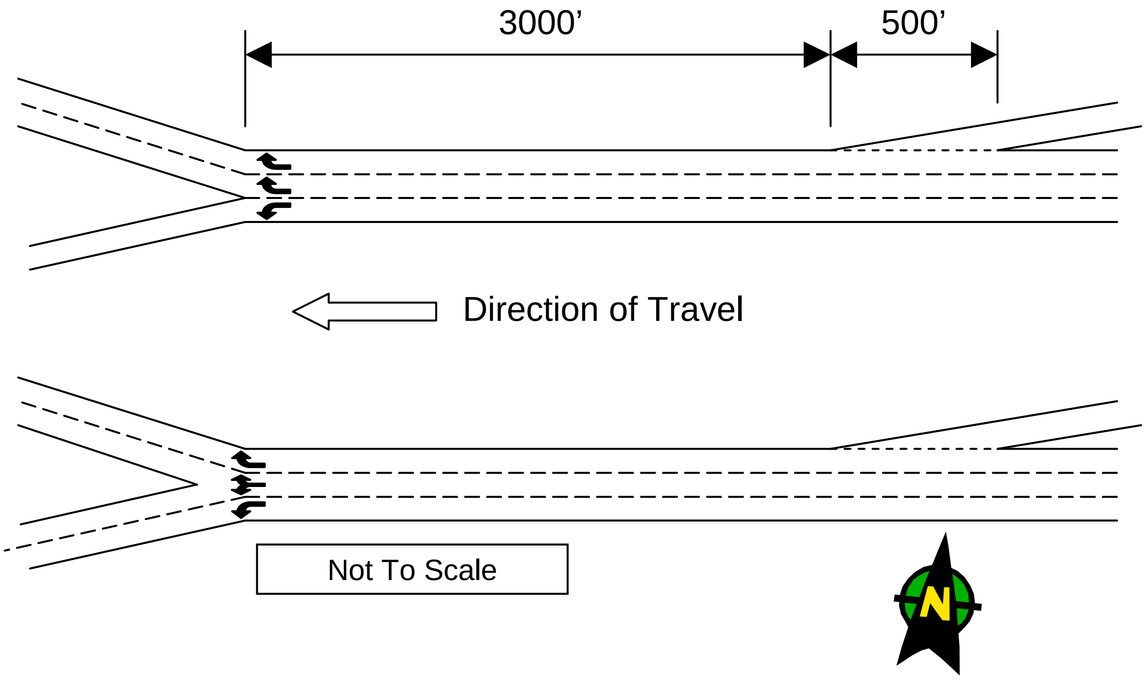


FIGURE 9 Hale Interchange weave section.

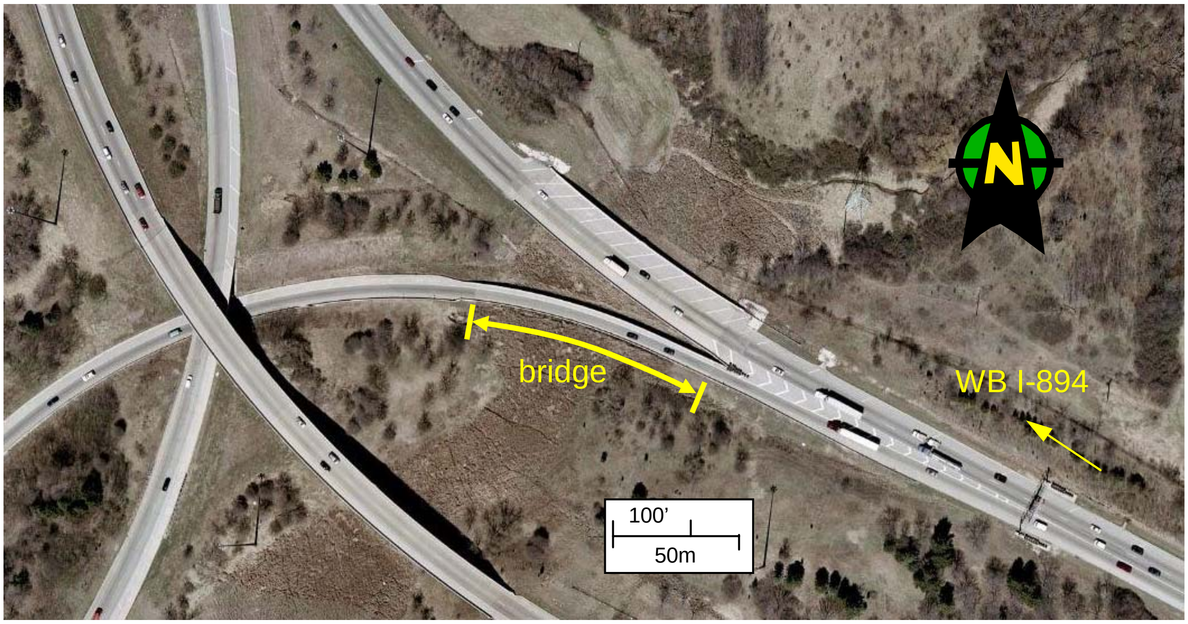


FIGURE 10 Westbound I-894 Hale Interchange ramp.

Because the terminal of the downstream end of the ramp widens to two lanes, there would be no need to make changes on the merge area at the ramp’s end. This treatment resulted in only 2 of the 10 VISSIM replications showing a bottleneck, as opposed to 9 of 10 in the baseline conditions. It is worth noting that the treatment resulted in an increase in bottleneck activation downstream at the Lincoln Ave. merge, discussed below, from 6 of 10 to 9 of 10.

An initial treatment was modeled and replicated that widened the ramp from the diverge gore to the viaducts, which is approximately 800’, shown below in Figure 11. The intention was to remove queuing from the downstream freeway and therefore at least provide improvement for the mainline through traffic. However, this was not enough storage space for the queues, so the location still qualified as a recurring bottleneck.

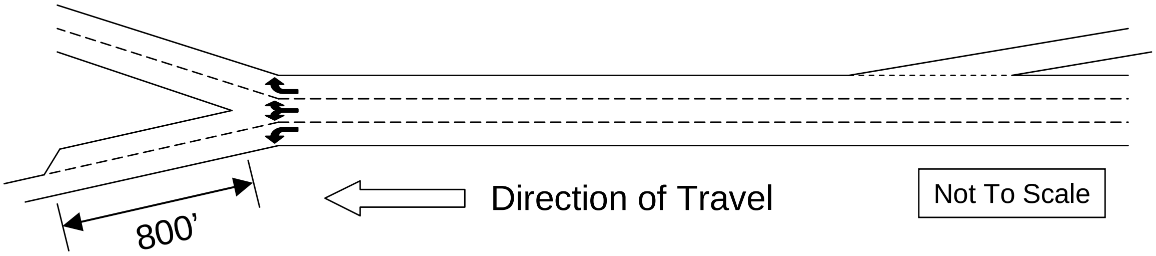


FIGURE 11 Initial proposed Hale interchange treatment.

Segment 31 (On-Ramp Merge – Lincoln Ave) Figure 11 shows the baseline geometrics of the Lincoln Ave. and Greenfield Ave merge areas. The treatment applied for the Lincoln Ave merge is the auxiliary lane addition between the Lincoln Ave. on-ramp and the downstream off-ramp. The distance between the two ramps is approximately 3150'. This lane addition can be accomplished through restriping without narrowing the lanes.

This treatment removed bottleneck activations at the Lincoln Ave merge in all of the VISSIM replications and the FREEVAL model. The bottleneck downstream at the EB Greenfield Ave. merge was activated 8 of 10 replications with this treatment as opposed to the 6 of 10 replications under baseline conditions. This would be expected as traffic upstream of the EB Greenfield Ave. merge is able to flow more freely with less obstruction. The treatment also created an active bottleneck in the FREEVAL model at the EB Greenfield Ave. merge.

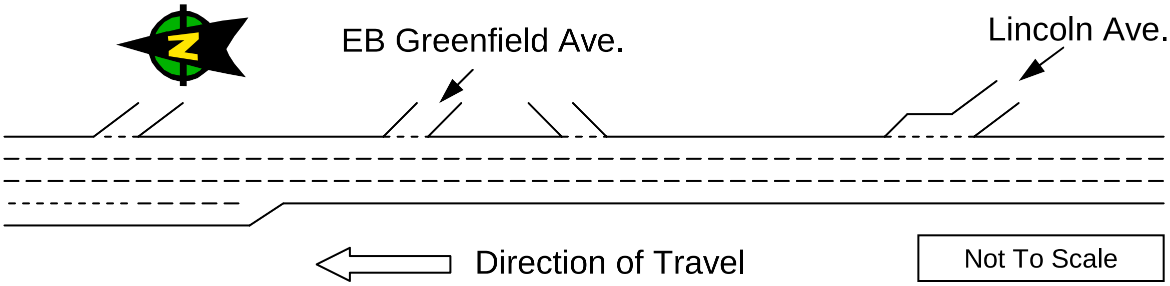


FIGURE 12 Lincoln Ave. and EB Greenfield Ave. merge areas.

Segment 34 (On-Ramp Merge – EB Greenfield Ave) A schematic diagram of the baseline conditions of this merge area are shown above in Figure 12. As can be seen in the figure, a left-side lane add already exists downstream of the ramp gore. This added lane becomes a freeway-to-freeway ramp in the Zoo interchange, hence the change in lane marking in the diagram. The treatment applied for this bottleneck was to simply extend the downstream lane-add to 1,000’ upstream of the EB Greenfield Ave. on-ramp gore. This treatment could be applied via restriping.

The applied measure resulted in no bottleneck activations in all 10 of the VISSIM replications and in the FREEVAL model.

Treatment Combination Effects No individual treatment targeted at a specific bottleneck location produced model results that significantly improved the modeled system beyond the targeted location. Two system-wide treatments were modeled and are discussed in the following paragraphs.

Hale Interchange – Lincoln Ave. – Greenfield Ave. This treatment combines the individual treatments applied at the Hale Interchange, Lincoln Ave., and Greenfield Ave. bottleneck locations earlier described.

The treatment at the Hale Interchange is exactly as previously described and shown in the bottom diagram of Figure 9.

The treatments of the Lincoln Ave merge and EB Greenfield Ave merge are slightly different than the first treatments described above. Figure 12, located on the previous, shows a schematic diagram of the baseline set-up. Displayed below in Figure 12 is a schematic diagram of the system treatment that was applied.

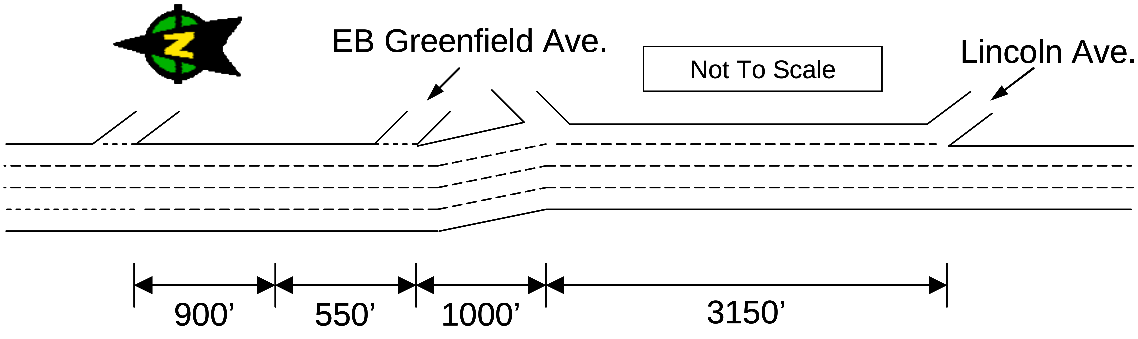


FIGURE 13 Lincoln Ave and EB Greenfield merge area system treatment.

The treatment involves changing the Lincoln Ave. on-ramp parallel acceleration lane to an added lane. Upon reaching the downstream off-ramp, instead of dropping the lane, as done when only treating the Lincoln Ave. merge, the lane continues and becomes the far right lane at the EB Greenfield Ave. on-ramp gore by way of lanes shifting. Through existing ample shoulder space and the fact that the ramps are taper type ramps, this can be accomplished through restriping. The benefit of this as opposed to simply combining the individual bottleneck treatments is a reduction in lane changing and a more even and stable flow.

System Fixed Time Ramp Metering Adding pre-set fixed time ramp meters to all on-ramps, with the exception of freeway-to-freeway ramps, resulted in a minor reduction of the overall number of bottleneck activations. Only 2 of the original 5 predicted recurring bottlenecks in VISSIM were no longer categorized as recurring with the ramp metering in place. The type

A weave at segment 3 (27th St interchange) increased its number of bottleneck qualifying replications from 7 to 9 out of 10.

In the FREEVAL model bottlenecks were still predicted at the Hale Interchange and 27th St. weave type A with ramp metering in place. Queuing was not predicted at any of the other previously discussed locations.

Missouri Site

Northbound I-270 Segment 13 (On-Ramp Merge) The treatment applied at this bottleneck location was the addition of an auxiliary lane extending to the following downstream off ramp. The original condition is shown in Figure 14A with the auxiliary lane treatment shown in Figure 14B. Because the ramps are approximately 3,600’ apart, adding the auxiliary lane would not create a weaving segment by Highway Capacity Manual standards. Therefore, adding the downstream off-ramp to the model is not necessary. While the construction of an additional lane is perhaps not a low-cost solution, it will provide a comparison of conditions if a lane was simply added.

In both FREEVAL and VISSIM, the additional capacity removed the bottleneck and vehicles traveled near or at free-flow speed. The addition of the auxiliary lane removed all congestion in the northbound direction (segments 13 and 10) in the FREEVAL model and in the VISSIM model. It is worth noting, the congestion in segment 5 (weave type B) of Eastbound I-44 is removed through this treatment in the VISSIM model. So while this represented a more expensive treatment, the additional capacity removed congestion on two different freeways.

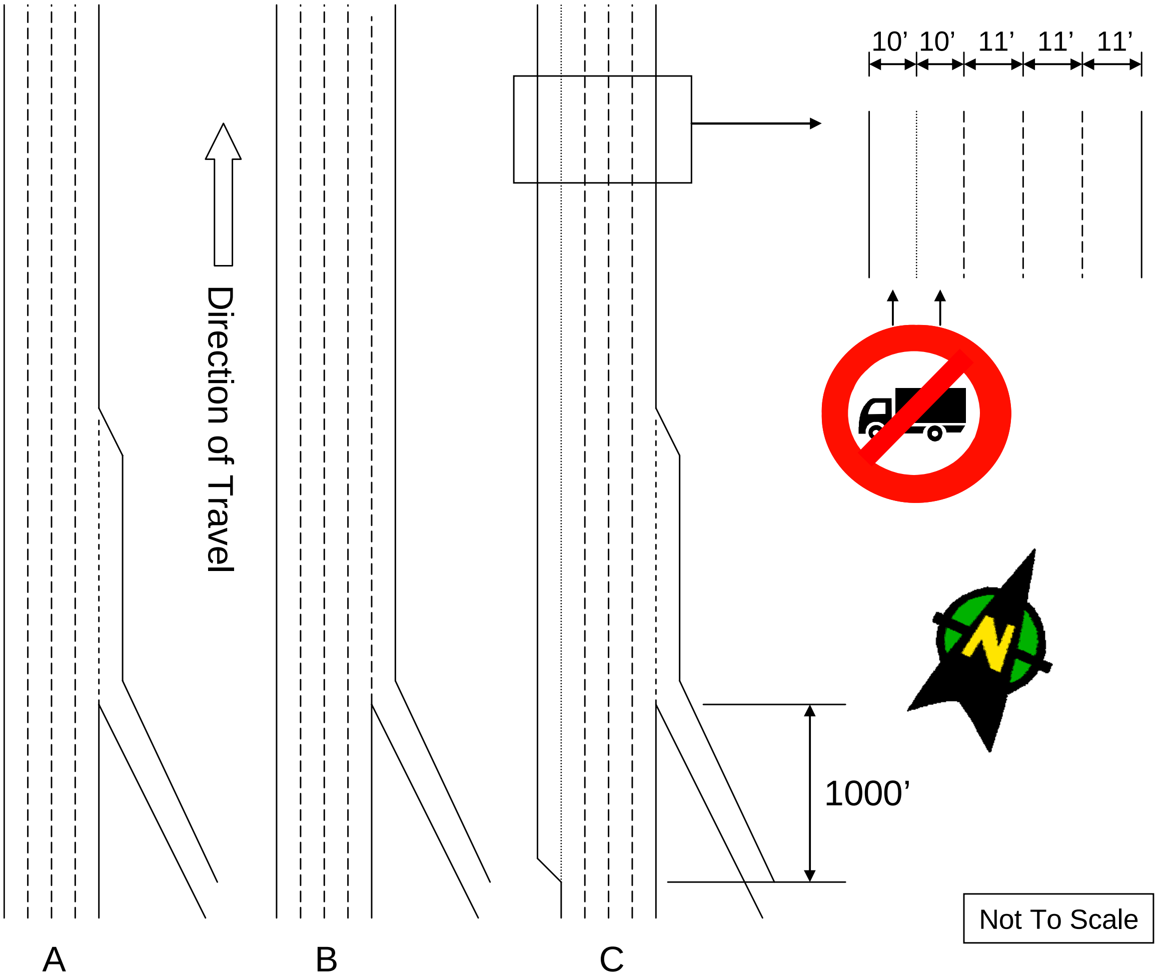


FIGURE 14 NB I-270 Segment 13 bottleneck treatments.

The final treatment applied to this bottleneck location involves restriping and adding a plus lane on the left that are open only during heavy demand periods, shown in Figure 14C. The restriping and plus lane modeling were implemented starting approximately 1,000 feet upstream of the segment 13 on-ramp gore. This treatments has been shown to significantly reduce the delay caused by the bottleneck however does not alleviate the bottleneck at this location. The bottleneck at this segment was still active in all 10 of the VISSIM of the replications; however, it did remove the congestion upstream on NB I-270 segment 10 and the recurring bottleneck on segment 5 of EB I-44. In VISSIM, this treatment was carried out by narrowing the lanes, adding speed reduction zones based on the lane adjustment factor in the HCM, and adding pre-timed signals in the added left lane spaced approximately 25’ apart. The plus lane treatment did remove the bottleneck in the FREEVAL model.

Northbound I-270 Segments 10 (On-Ramp Merge) The addition of the auxiliary ramp downstream and the restriping and plus-lane treatment at segment 13 on-ramp merge removed the bottleneck at this location in FREEVAL and all VISSIM replications. Also, the system ramp metering treatment removed the bottleneck at this location in all VISSIM replications. Even though no specific treatments were modeled at this segment, two treatments initially intended to primarily remove the downstream bottleneck, removed the congestion on this segment.

Because this bottleneck did not activate once the downstream queue was removed, this segment was not by definition a recurring bottleneck under baseline conditions. Had the bottleneck at this segment still been present after the downstream queue was removed, that would have indicated this was a hidden bottleneck.

Southbound I-270 Segment 3 (Off-Ramp Diverge) Congestion at this segment was thought to be exacerbated and possible caused by queuing in the right lane for the downstream off-ramp lane drop at segment 5. Because of this, the off-ramp at segment 5 was widened to two lanes in order to make storage room on the ramp in order to avoid spillback onto the freeway as shown in Figures 15A and 15B. While the desired results were achieved at the segment 5 off-ramp lane drop, analysis shows that the treatment did not alleviate the bottleneck at segment 3, as it was activated in 6 of 10 VISSIM replications.

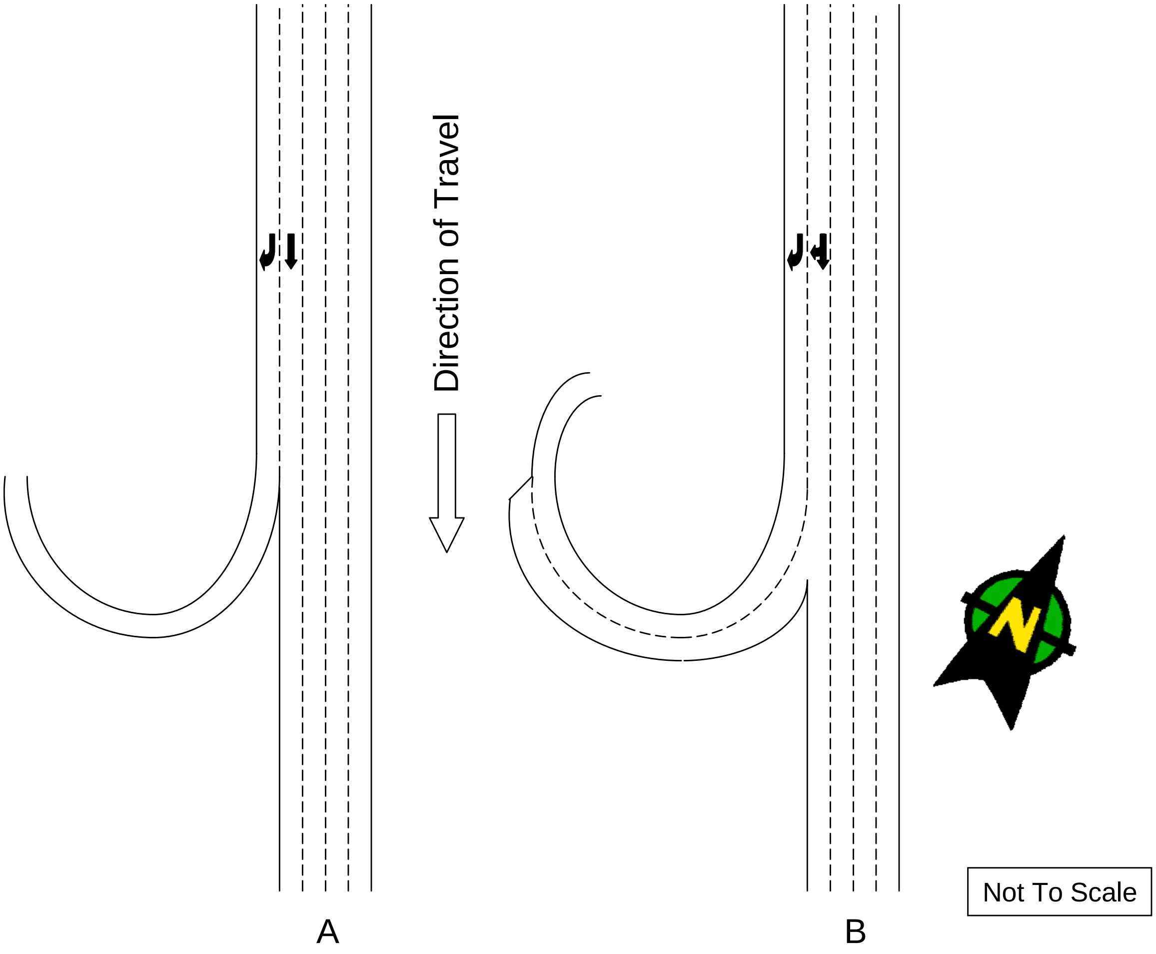


FIGURE 15 SB I-270 Segment 5 off-ramp baseline and treated conditions.

The segment 3 off-ramp was expanded to a 2 lane off ramp and analysis has shown that this has alleviated the bottleneck at this location. The baseline and treated conditions are shown in Figures 16A and 16B respectively. The far right lane of the freeway is an exit only lane and the 2nd lane was converted to a through-exit lane. Therefore, the only additional construction necessary would be the widening of the ramp. However, since the paved area of the ramp is approximately 30’ wide, it might be possible to restripe and achieve the same results without additional construction.

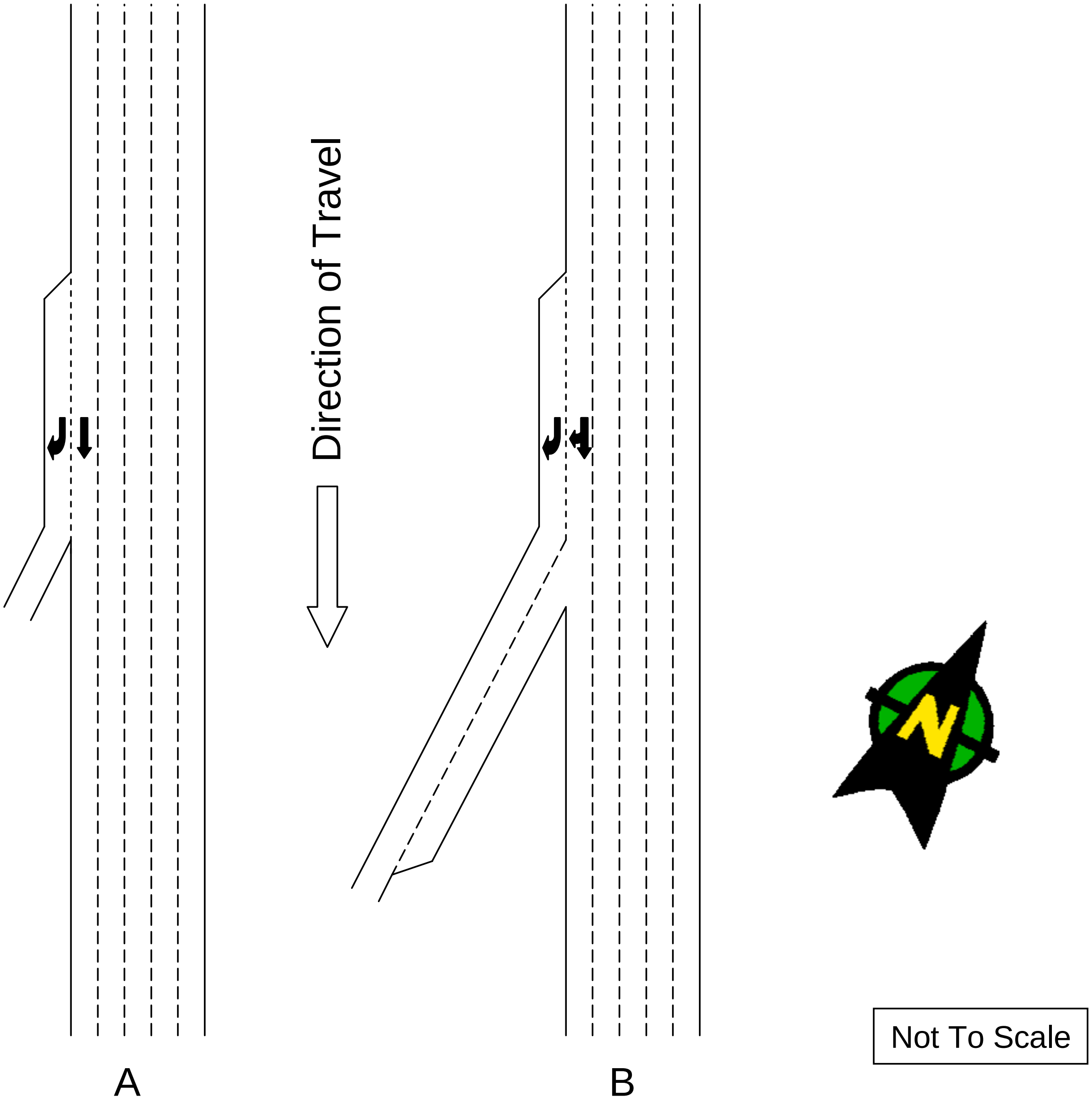


FIGURE 16 SB I-270 segment 3 off-ramp baseline and treated conditions.

Since there were no on-ramps within the modeled network upstream of these two off-ramps, ramp metering would not be a viable treatment.

It is worth noting, as shown in Table 6, that the number of replications with bottleneck activations at this segment increases for treatments that were not applied at this segment in the VISSIM model. This phenomenon simply demonstrates the effect of model stochasticity on the results, even though the same random seeds were used for each scenario's ten replications.

Eastbound I-44 Segment 5 (Weave Type B) System-wide ramp metering（Meters at Northbound I-270 segments 2 and 13, Eastbound I-44 segment 5 On-Ramp, and Westbound segment 5 Off-Ramp as shown in Figure 4) did not completely remove the bottleneck at this location. A bottleneck was still active at this segment in 4 of 10 VISSIM model replications. Since it is only active in 40% of the replications, it does not qualify as a recurring bottleneck location.

The congestion at this segment was shown to be completely alleviated with the addition of an auxiliary lane and a plus lane at segment 13 of NB I-270 described above. There were no active bottlenecks at this location in any replications with either treatment.

Similar to SB I-270 segment 5, and as shown in Table 6, the number of replications with bottleneck activations at this segment changes for treatments that should have had no effect on the traffic conditions at this location in the VISSIM model.

No treatments specific to this segment were modeled. This recurring bottleneck was created by congestion elsewhere on the network, so once that was treated, the bottleneck was removed.

Ramp Metering Ramp meters were placed at the affecting ramps in the models (Northbound I-270 segments 2 and 13, Eastbound I-44 segment 5 on-ramp, and Westbound segment 5 off-ramp shown in Figure 4) and replicated in FREEVAL and VISSIM. Metering was found to improve the conditions, however does not significantly alleviate the bottleneck at this location as it was still activated in 9 of 10 VISSIM replications. No bottlenecks were removed in FREEVAL with ramp metering. While the ramp metering did not remove the bottleneck at this location, it did remove the congestion upstream at segment 10 and the recurring bottleneck at segment 5 on Eastbound I-44. This indicates that the ramp and mainline demands of the segment are too high to be treated by ramp metering alone without creating severe congestion on the surface streets.

Summary of Results

Tables 6 and 7 summarize the frequency of bottleneck activations in the model replications of the Missouri site. Tables 8 and 9 summarize the frequency of bottleneck activations in the model replications of the Wisconsin site. Table cells with an asterisk indicate bottleneck locations that are expected to directly benefit from the applied treatment.

Missouri Site

While all treatments resulted in some improvement on at least one identified recurring bottleneck site, the auxiliary lane constructed at NB I-270 segment 13 and downstream, generated the most improvement as it removed all bottleneck activations from 2 segments in VISSIM and 1 segment in FREEVAL. So, as a systems approach, that treatment provided the most benefit, as it resulted in only 5 bottleneck activations in the VISSIM model and 0 activations in the FREEVAL model. Intuitively this is the treatment that would be expected to provide the greatest benefit as it would appear to add the most capacity. As shown in Table 7, the FREEVAL model never predicted more than one bottleneck in a single run of the Missouri site.

Because the congested conditions on NB I-270 segment 10 were determined not to be caused by a bottleneck on that segment, the tables show that a bottleneck was never activated in any of the replications.

In Tables 6 and 7, a pair of measures of effectiveness (MOE) is shown as well. The two MOE's shown are average freeway vehicle miles traveled (VMT) and average freeway through travel time. As seen in both tables, and as would be expected, the treatment(s) with the fewest bottleneck activations have the lowest corresponding average freeway through travel time. Somewhat surprisingly, even though the system ramp metering treatment showed the smallest reduction in bottleneck activations, in the VISSIM model, it produced the 2nd largest reduction in average freeway through travel time and the 2nd smallest standard deviation in average freeway through travel time. This demonstrates that while ramp metering may not remove an active bottleneck it can significantly improve travel time and travel time predictability.

TABLE 6 Bottleneck Activations and other MOE's in 10 Replications of the VISSIM Model – Missouri Site

Baseline Recurring Bottleneck Location	Baseline Model	System Ramp Metering	NB I-270 Segment 13 Aux. Lane	NB I-270 Segment 13 Plus Lane	SB I-270 Segment 3 Off-Ramp Widening	SB I-270 Segment 5 Off-Ramp Widening
NB I-270 Segment 13	10/10	9/10*	0/10*	10/10*	10/10	10/10
NB I-270 Segment 10	0/10	0/10	0/10	0/10	0/10	0/10
SB I-270 Segment 3	5/10	5/10	6/10	5/10	0/10*	6/10*
EB I-44 Segment 5	7/10	4/10*	0/10	0/10	5/10	4/10
Total Bottleneck Activations	22	18	6	15	15	20
Average Freeway VMT (Std. Dev.)	197,028 (1,347)	182,494 (511)	186,343 (2,602)	176,483 (382)	182,827 (1,266)	181,289 (8,751)
Average Freeway Through Travel Time (Std. Dev.) (mins)	5.685 (0.325)	05.713 (0.157)	5.442 (0.058)	5.682 (0.108)	05.620 (0.110)	05.615 (0.072)

** Bottleneck location directly targeted by treatment*

TABLE 7 Bottleneck Activation and other MOE's in FREEVAL Model – Missouri Site

Baseline Recurring Bottleneck Site	Baseline Model	System Ramp Metering	NB I-270 Segment 13 Aux. Lane	NB I-270 Segment 13 Plus Lane	SB I-270 Segment 3 Off-Ramp Widening	SB I-270 Segment 5 Off-Ramp Widening
NB I-270 Segment 13	Yes	Yes*	No*	No*	Yes	Yes
NB I-270 Segment 10	No	No	No	No	No	No
SB I-270 Segment 3	No	No	No	No	No*	No*
EB I-44 Segment 5	No	No*	No	No	No	No
Total Bottleneck Activations	1	1	0	0	1	1
Freeway VMT	190,545	190,545	190,982	190,982	190,545	190,545
Freeway Average Through Travel Speed (mins)	05.770	05.770	05.548	05.548	05.770	05.770

** Bottleneck location directly targeted by treatment*

Wisconsin Site

Similar to the Missouri site, all modeled treatments resulted in an improvement on at least one identified recurring bottleneck location, as seen in Tables 8 and 9. The combined treatment of the Hale interchange and Lincoln and Greenfield on-ramp merges, resulted in the best overall results in both the FREEVAL and VISSIM model based on bottleneck activations, average VMT, and average travel time. It is worth noting, that VISSIM eventually identified the Segment 13 on-ramp merge as a hidden bottleneck, and FREEVAL did not.

Also similar to the Missouri site, the system ramp metering treatment showed the smallest reduction in bottleneck activations (Table 8) in the VISSIM model. Likewise, it produced the 2nd largest reduction in average freeway through travel time and the 2nd smallest standard deviation in average freeway through travel time. This reiterates the statement that while ramp metering may not remove active bottlenecks, it can significantly improve travel time and travel time predictability. At the Milwaukee, WI site however, the ramp metering did show the 2nd largest reduction in average freeway travel time in the FREEVAL model, behind the combined treatment of the Hale Interchange, and Lincoln and Greenfield on-ramp merges.

TABLE 8 Bottleneck Activations and other MOE’s in 10 /Replications of VISSIM Model – Wisconsin Site

Baseline Recurring Bottleneck Location	Baseline Model	27th St: Extend Accel. Lane (WB)	27th St: Ramp Closure	Loomis Rd: Aux. Lane (WA)	Hale Interchange: Weave Reduction and Off-Ramp Widen	Lincoln Ave: Aux. Lane (WA)	Greenfield Ave: Lane Add	Hale/Lincoln/ Greenfield Treatments	System Pre-Set Ramp Metering
Segment 1 Basic	1/10	2/10	0/10	1/10	1/10	1/10	1/10	1/10	1/10
Segment 3 Weave A	7/10	0/10*	0/10*	7/10	7/10	7/10	7/10	7/10	9/10
Segment 7 On-Ramp Merge	0/10	0/10	0/10	0/10	0/10	0/10	0/10	0/10	0/10
Segment 10 On-Ramp Merge	10/10	10/10	10/10	0/10*	10/10	10/10	10/10	10/10	10/10
Segment 13 On-Ramp Merge	1/10	2/10	0/10	6/10	1/10	1/10	1/10	1/10	1/10
Hale Interchange Weave	9/10	9/10	8/10	10/10	2/10*	8/10	9/10	2/10*	8/10
Segment 31 On-Ramp Merge	7/10	6/10	6/10	6/10	9/10	0/10*	8/10	0/10*	4/10
Segment 34 On-Ramp Merge	5/10	8/10	8/10	6/10	6/10	8/10	0/10*	0/10*	4/10
Total Bottleneck Activations	40	37	32	36	35	35	36	25	37
Average Freeway VMT (Std. Dev.)	117,929 (433)	117,145 (334)	117,635 (424)	117,928 (430)	117,928 (435)	117,928 (433)	117,920 (433)	116,299 (432)	117,892 (475)
Freeway Average Through Travel Time (Std. Dev.) (mins)	11.242 (0.133)	11.115 (0.133)	11.252 0.200)	11.138 (0.165)	11.113 (0.153)	11.190 (0.163)	11.178 (0.138)	10.658 (0.080)	11.067 (0.127)

** Bottleneck location directly targeted by treatment*

TABLE 9 Bottleneck Activations and other MOE's in FREEVAL Model – Wisconsin Site

Baseline Recurring Bottleneck Location	Baseline Model	27th St: WB	27th St: Ramp Closure	Loomis Rd: WA	Hale Interchange: Weave Reduction and Off-Ramp Widen	Lincoln Ave: WA	Greenfield Ave: Lane Add	Hale/Lincoln /Greenfield Treatments	System Pre-Set Ramp Metering
Segment 1 Basic	No	No	No	No	No	No	No	No	No
Segment 3 Weave A	Yes	No*	No*	Yes	Yes	Yes	Yes	Yes	Yes
Segment 7 On-Ramp Merge	No	Yes	Yes	No	No	No	No	No	No
Segment 10 On-Ramp Merge	Yes	Yes	Yes	No*	Yes	Yes	Yes	Yes	Yes
Segment 13 On-Ramp Merge	No	No	No	No	No	No	No	No	No
Hale Interchange Weave	Yes	Yes	Yes	Yes	No*	Yes	Yes	No*	Yes
Segment 31 On-Ramp Merge	No	No	No	No	Yes	No*	No	No	No
Segment 34 On-Ramp Merge	No	No	No	No	Yes	No	No*	No	No
Total Bottleneck Activations	3	2	3	2	4	3	3	2	3
Freeway VMT	115,412	115,418	115,307	115,414	115,412	115,412	115,412	115,412	115,412
Average Freeway Through Travel Time (mins)	10.707	10.673	10.670	10.663	10.507	10.647	10.665	10.377	10.492

** Bottleneck location directly targeted by treatment*

VIII. ASSESSMENT OF MODELING TOOLS

In this study, two analysis tools, VISSIM and FREEVAL were used to model freeway facility operations and analyze potential low cost, recurring bottleneck mitigation measures. For future studies, it is important to offer an analysis based on the experience gained by running the models and their ability to realistically estimated performance before-and-after treatments in this study.

As a starting point, the importance of a well calibrated model can not be overstated. However, because a calibration can only be commensurate with the accuracy of the available data and information, a high level of accuracy is not always possible. The confidence in the model is something to keep in mind when examining the results of both the baseline and treatment model results.

Also, it is important to understand the limitations and capabilities of a model when examining the results. As shown throughout the report, the qualities of the models played a significant part in the bottleneck identification process.

Tables 10 and 11 summarize and compare some of the different characteristics of VISSIM and FREEVAL. Table 10 displays the modeling capabilities of the models, and Table 11 shows the user investments necessary such as required model inputs and data processing needs. Some of these aspects are discussed further in the following paragraphs.

TABLE 10 VISSIM and FREEVAL Model Capabilities Summary

ITEM		VISSIM	FREEVAL
Bottleneck Identification Capability	Active Bottlenecks	From processed output only	d/c > 1.0; upstream queue present
	Hidden Bottlenecks	Requires multiple runs to reveal hidden bottleneck after active one(s) is treated	d/c > 1.0; no upstream queues; active upstream bottleneck
	Speed profiles	From processed output only	In standard output
	Drop in mainline throughput upon queue formation	Can be modeled	Cannot be currently modeled
Types of Recurring Bottlenecks that can be modeled	Heavy on-ramp demand	Can be modeled	Can be modeled
	Weaving Sections	Can be modeled	Can be modeled (Types A, B , C only)
	Heavy off-ramp demand causing spillback on mainline	Can be modeled	Cannot be modeled
	Lane drops	Can be modeled	Can be modeled
	Tunnels and bridges	Coded as speed reduction zone and/or user-defined link type, resulting in reduced capacity	Coded as reduced capacity via capacity adjustment factor (CAF)
	Horizontal and vertical Curves	Grades can be input. Coded as speed reduction zone and/or user-defined link type.	Grade effect on capacity can be modeled
	Narrow lanes/ lateral obstruction	Coded as speed reduction zones and/or user-defined link type	Reduces FFS, and capacity using HCM models
	Inadequate accel/decal Lanes	Can be modeled in detail	Affects density in ramp influence areas
Types of Low Cost Treatments that can be modeled	Auxiliary lanes	Can be modeled	Can be modeled
	Peak-hour or plus lanes	Modeled using time-dependent signal, parking spaces, or transit stops	Can be modeled
	Paved shoulders	Can be modeled	Can be modeled as reduced capacity lanes
	Re-striping ; add narrow lanes	Modeled as reduced speed zones	Modeled as reduced capacity lanes
	HOV lanes	Can be modeled	Cannot be modeled
	Truck restrictions	Can be modeled	Cannot be modeled
	Ramp metering	Can be modeled—some bugs exist	Can be modeled at macro level only
	Temporary ramp closures	Can be modeled- traffic manually reassigned	Can be modeled- traffic manually reassigned
	Traffic diversion information	Cannot be modeled—manual diversion only	Cannot be modeled—manual diversion only
	Exit ramp widening	Can be modeled	Can be modeled, but has no impact

TABLE 11 VISSIM and FREEVAL Model User Investments Summary

ITEM		VISSIM	FREEVAL
Required Model Inputs	Time-Varying Traffic Demands	Mainline, on- ramp demands; O&D volumes	Mainline and on-ramp demands
	Link geometry attributes	Flexible and user defined	HCM segment types only
	Variable Link FFS	Coded as speed zone if variable	HCM FFS speed estimation equation
	Vehicle types	4 pre-set and more can be user-defined	Cars, Trucks, RV's
	Ramp geometry	Detailed	Ramp FFS and lanes
	Single/Multiple Facilities	Allows single or multiple	Directional Facilities only
	Single/Multiple time intervals	Allows both	Allows Both
Input and Output Data Processing and Model Calibration	Ease of input coding	Simple, but time consuming – WI case study input required 8-10 hours	Very quick input process; WI case study input required 10-15 minutes
	Model calibration scope	Multiple calibration parameters	Handful of calibration parameters
	Bottleneck identification process in the model	Requires detailed output processing of link by link speed	Requires no additional processing of output
	Number of runs required	Minimum of 10 replications are needed	Macroscopic- single replication
	Quality of output related to fidelity of treatment impact	High fidelity with calibrated model	Medium fidelity with calibrated model
	Model running time (see page 16 for computer specs)	0.7 hours per replication for WI site, total 6.7 hours	1-2 minutes per run- no replications

VISSIM

VISSIM's flexibility as a microsimulation tool proved very useful throughout this study. Comments regarding the modeling of the treatments will be offered in the following paragraphs. Statements regarding the quantitative accuracy of the treatments will be avoided since empirical data were not available for most treatments.

The input coding of a VISSIM model is not particularly difficult. However, the process is much more time intensive than that of FREEVAL. As a point of reference, the Milwaukee, WI site, a unidirectional 10 mile facility, is estimated to have taken approximately 8-10 hours to model, whereas it would only take approximately 10-15 minutes to create the same model in FREEVAL. This time does not include the time required for replication, calibration, or data collection. The number of required inputs is greater in both CORSIM and VISSIM. The number of minimum inputs required for a modeled network varies greatly depending on the scope of the network and what traffic operation features are to be included.

Because VISSIM has many default input values, a user would minimally need to enter the roadway geometry using appropriate link types, vehicle network inputs and paths (origin-demand matrices), traffic control devices, and signal timing plans. Information regarding link types, vehicle classes and types, traffic types, desired speed distributions, lane-changing behavior and car-following behavior parameters have pre-set defaults, but can be adjusted by the user for greater accuracy and control. Features used in this study that are not necessarily required inputs include reduced speed zones and speed decisions. All of the features and inputs mentioned in the preceding text each have multiple of available inputs and parameters that can be adjusted so that the user can create as accurate of a model as desired.

VISSIM does not adjust the drivers' desired speed based on lane width. Therefore, if it is desired to model traffic slow down because of lane narrowing, creating reduced speed zones is necessary. A slow down in VISSIM will generally result in a reduction in link capacity. If the reduced speed does not impact link capacity as the user desires and/or appropriate data are available, it would be possible to create a special link type and adjust the parameters in order to set the link capacity to the desired amount. The VISSIM model appears to perform in a manner that would be expected when narrow lanes and reduced speed zones are created.

Regarding the treatment of widening an off-ramp, VISSIM again performed as would be expected. When widening the ramp, it is important to pay attention to the route lane change distance of the link connectors. This distance determines when the vehicles will begin to attempt a lane change *(26)*. This could be set to a distance used throughout the model or the location of a sign for example.

Treatments that incorporated the addition, change of type, or removal of weaving sections did not seem to require any additional changes other than the necessary link lane changes. This is what would be expected since the model is driven by driver behavior algorithms.

Pre-set fixed time ramp metering was the only ramp metering treatment implemented. This was carried out using the NEMA signal controller and reduced speed zones in VISSIM. As mentioned earlier, through this study it was found that the VISSIM controller could not generate non-integer cycle lengths. This does not allow for precise ramp meter control. The use of reduced speed zones as ramp meters was thought of when the meter performance was observed to be unreliable for situations where it was desired for more than one vehicle to proceed for each green indication. This strategy induces delay through speed reduction and was found to provide a precise and accurate method. The main drawback to this method is that the physical signal placement is not modeled. Regardless, if the downstream end of the speed zone is compliant with AASHTO acceleration distance guidelines, then the model should still provide reliable results. The other issue that some may rise with this method, is that it does not necessarily create true queuing in the same fashion that an actual signal would.

Another modeling issue uncovered while using VISSIM was the modeling of temporary lanes. Several methods were attempted, and selected method used was to place signals on the freeway lane that had a green signal indication only during certain times in the simulation (when the lane was to traffic). As previously discussed, other methods are available and a utility is under development to better model temporary lane closures and openings. However, current methods are cumbersome, and most likely do not provide results with a desired level of precision.

VISSIM was unable to provide data or information that would support or disprove a hypothesized hidden bottleneck location. Using available methods, the most effective way of identifying hidden bottlenecks in the VISSIM is to treat an existing recurring freeway bottleneck in a series of runs and determine whether a new bottleneck appears downstream of the treated location in a second set of runs.

Identifying active bottlenecks in VISSIM is a little more complicated than in FREEVAL because of the nature of the VISSIM output. VISSIM's outputs are provided in a text file. For an experienced VISSIM user, identifying active bottlenecks can prior to processing the data file, assuming the user is focusing on specific (suspect) links. However, if the user is trying to identify active bottlenecks without any prior knowledge of where active bottlenecks are, processing the text file would need to be completed to identify active bottleneck locations. Initial processing can take upwards of 4 hours to extract the desired performance measures. However, once data reduction system has been created, processing a set of 10 runs can be completed in as little as 20 minutes.

While a large number of performance measures are available from the VISSIM model, only link evaluation outputs were selected to be recorded in this study. VISSIM provides the outputs in text files that require the user to manipulate and process the data to the user's requirements. An example of the output is shown in the Appendix B on page 100. This example depicts the header and first few lines of the VISSIM output file. Had the entire file been included, it would have been over 70 pages in length. This process can be somewhat time consuming and tedious, and because of multiple replications per model configuration, extracting results and model calibration are not trivial tasks. This, in conjunction with the time it can take to run one replication, can make the entire VISSIM modeling process very time intensive. In this study, the MO site require approximately 70 minutes per replication, while the WI site required 40 minutes. The simulation time seems to depend greatly on the size, complexity, and intensity of traffic flow of the network.

FREEVAL

FREEVAL's deterministic nature allowed for most treatments to be modeled in a very straight forward manner. The inputs required are relatively minimal compared to VISSIM and CORSIM and take approximately 5 to 10 minutes to enter depending on the size of the modeled facility and the analysis period. A model can be replicated with as little information as mainline and lane volumes, FFS, segment type and number of lanes. In addition, capacities can be altered from the baseline HCM values using a capacity adjustment factor on any segment. Further auxiliary lanes can be added during specific time intervals (e.g. the plus lane), and the model allows for simplified ramp metering in which queues can build on the on-ramp roadway although the queue does not propagate to the surface street ramp interface.

As discussed in earlier chapters, since FREEVAL cannot model capacities of off-ramps, the modeling of off-ramp treatments was not possible in the FREEVAL model.

Modeling narrower lanes through restriping is carried out through by entering the new lane and clearance widths. FREEVAL uses HCM methodologies to adjust the FFS curve and segment capacity. Capacity can also be altered using the capacity adjustment factor, as stated above.

Treatments that incorporated the addition, change of type, or removal of a weaving section did not seem to require any additional changes other than adjusting the number of lanes in the appropriate segments and changing the segment type. FREEVAL adjusts the capacities of the segments as per HCM methodologies. In some instances, the addition or subtraction of a segment may be necessary. Because FREEVAL will change the capacities depending on the segment type, it may not be necessary to change the baseline calibrated capacity adjustment factors. The decision to change the capacity adjustment factor based on segment type should be based on the level of field data available.

Ramp metering treatments in FREEVAL can only be modeled at a fixed capacity for each time period. The benefit of freeway flow stabilization from ramp meters is not experienced in FREEVAL. The process is simple, and complex metering strategies (e.g. platoon metering) are not available.

FREEVAL's ability to output segment demand and volume along with multiple performance measures allows for easy identification of active and hidden bottlenecks. The ease of identification means that a modeler can accurately predict the system wide effects of treatments before adding the treatment into the model or field. Examples of the FREEVAL summary output are on pages 98 and 99 in Appendix B. The example output on page 99 does not show the entire modeled network and is intended to show FREEVAL's ability to communicate hidden bottleneck's to the user. As shown, in Segments 31 and 34, the d/c ratio is greater than 1, however there is no queuing. This indicates a hidden bottleneck.

The outputs of the FREEVAL model are reported in tables and graphs that are fairly intuitive. No manipulation or processing of the data and information is necessary to put it in an easy to read format. The replicating of the model itself typically takes less than a minute, and since only one replication is needed, the time required to model, replicate, and analyze a unidirectional freeway facility is approximately 20 minutes.

Summary and Recommendations

While both the tested models can predict system-wide effects of a recurring bottleneck treatment, FREEVAL's ease of use, relatively short modeling and analysis time, and its ability to quickly show active and hidden bottlenecks, demonstrate that it is better suited for modeling existing conditions and exposing locations where problems may arise. The model complexity and flexibility of VISSIM make it a better tool for modeling proposed treatments and determining their effects on the entire network including surface streets.

It may be useful to consider a hybrid approach where FREEVAL is employed for active and hidden bottleneck identification, followed by the use of VISSIM runs to characterize system performance under baseline and treatment conditions. The VISSIM runs would also be used to identify freeway bottlenecks created by off-ramp spillback since FREEVAL does not have this facility at this time. A proposed plan to improve FREEVAL capabilities is attached in Appendix C.

It is recommended that a summary output feature be added to the VISSIM software package that is particularly geared toward bottleneck identification. The time required to process and analyze the performance of the VISSIM models would have been greatly reduced if a link evaluation summary output was available. Since the capability of outputting link density, volume, average vehicle speed, and other measures by user defined time periods exists, it would seem reasonable that summary outputs of selected links would be possible to incorporate. This feature would reduce the overall calibration process and treatment evaluation process significantly.

Another recommendation for the VISSIM model would be to include the ability to temporary close lanes. This feature would allow for the modeling of vehicle incidents and flexible lane operations, such as plus lanes.

IX. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

As stated in the introduction chapter, the primary objective of this thesis is to evaluate the abilities of analysis tools, in particular VISSIM and FREEVAL for the purposes of identifying active and hidden bottlenecks, and in modeling treatments for mitigating their effects and measuring their effectiveness.

Regarding both bottleneck activations and overall network congestion, it was found that FREEVAL predicts generally less congested conditions than does VISSIM. It appears that this is more of a function of the current limitations of FREEVAL than a difference in general performance. The additional congested locations reported by VISSIM were due to its ability to model off-ramp capacity constraints and spill back along with network interactions. This limitation in FREEVAL has been reported as a needed enhancement of this tool (see Appendix C). The definition of a recurring bottleneck appears to have worked reasonably well in the context of this case study.

The results demonstrate the importance of scanning the effect of local improvements throughout the network created by a treatment, and not just at the segment that the treatment is primarily intended for. In general, however both models responded in the right direction and the treatments improved performance. More importantly, a treatment often had an impact further upstream or downstream from where it was implemented, depending on the type and spatial extent of the treatment. This is evident from observing some of the results in, for example Tables 6-9. Applying a system-wide approach to the problem enables the analyst to gain such insights. As far as the merits of each approach (micro or macro) are concerned, it is evident that they both are able to identify the principal bottlenecks but differ in detecting secondary effects. The price of this added detection capability is obviously added resources in coding and extracting model output in the micro simulation model case.

Also demonstrated is the need to compare across models. The limitations and performances of the models indicate that one cannot necessarily depend on one single model, and that using a macro- and microsimulation model will provide both differing and complimenting results, that when coupled with engineering judgement, can provide a reasonable prediction of a system's performance.

Future Research

Despite the rather simplistic nature of the recurring bottleneck definition, accurate quantitative modeling of low-cost bottleneck treatments is the ultimate goal. This work has shown that bottleneck identification appears not to be problematic in a simulation environment. However, future research should focus on calibrating the effects of the improvements (e.g., narrow lanes, plus lanes, shoulder use, etc) on observed capacity, and verify the modeled treatment performance with comparable field observations.

Recommended future research focuses on model improvement. Throughout this paper limitations of the FREEVAL and VISSIM models have been discussed. However, while some of these limitations can easily be fixed using existing knowledge and methodologies (i.e. queue discharge rate), some require additional data collection and analysis.

Studies focusing on temporary lane capacities would provide information for the modeling of the use of plus-lanes and breakdown lanes during the peak traffic periods.

Modeling these types of lanes currently require either extensive knowledge of their operation for modeling or relying on capacity changes caused by reduced speeds. At current, the most relevant U.S. studies available are most likely those of construction zone capacities.

The most glaring opportunity that has been mentioned most throughout this paper is the modeling of off-ramp capacities in the FREEVAL model. The ability to input and model off-ramp capacity and storage is necessary, but also the development of a macroscopic model that can estimate the effects of off-ramp spillback without a lane-by-lane analysis. The addition of an off-ramp capacity model would allow for a more complete system analysis in the FREEVAL model. The formulation of such a model would require a certain amount of data collection and analysis for model calibration purposes

X. REFERENCES

1. Cambridge Systematics, Inc. and Highway User's Alliance. "Unclogging America's Arteries: Effective Relief for Highway Bottlenecks, 1999-2004." February, 2004.

2. Bertini, R. L. Toward the Systematic Diagnosis of Freeway Bottleneck Activation. Intelligent Transportation Systems, 2003. Proceedings. 2003 IEEE. Vol. 1, 2003. pp. 442-447.

3. Daganzo, C. F. *Fundamentals of Transportation Engineering and Traffic Operations.* New York, Elsevier Science. 1997.

4. Machemehl, R. G., T. W. Rioux, A. Tsyganov, and P. Poolman. Freeway Operational Flexibility Concepts. Center for Transportation Research. Research Project 0-1844 for TxDOT in cooperation with USDOT FHWA. Research Report 1844-1. March, 2001.

5. Walters, C. H., S. A. Cooner, and S. E. Ranft. Reconsidering Freeway Bottlenecks: Case Studies of Bottleneck Removal Projects in Texas. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1925*. TRB, National Research Council, Washington, D.C., 2005, pp. 66-75.

6. Walters, C. H. and S. A. Cooner. *Understanding Road Rage: Driver Irritants and Promising Mitigation Measures*. Publication TX-02/4945-3. Texas Department of Transportation, 2001.

7. Yagar, S. and R. Hui. Systemwide Analysis of Freeway Improvements. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1554*. TRB, National Research Council, Washington, DC, 1996.

8. *A Toolbox for Alleviating Traffic Congestion.* Institute of Transportation Engineers, Washington, D.C., 1989.

9. Piotrowicz, G. and J. Robinson. *Ramp Metering Status in North America: 1995 Update*. Final Report, FHWA, DOT-T-95-17, June 1995.

10. Banks, J. H. The "Two-Capacity" Phenomenon at Freeway Bottlenecks: A Basis for Ramp Metering? Presented at the 70th Annual Meeting, TRB, Washington, D.C., 1991.

11. Hall, F. L. and K. Agyemang-Duah. Freeway Capacity Drop and the Definition of Capacity. Presented at the 70th Annual Meeting, TRB, Washington, D.C., 1991.

12. Bertini, R. L. and A. M. Myton. Use of Performance Measurement System Data to Diagnose Freeway Bottleneck Locations Empirically in Orange County, California. *Transportation Research Board: Journal of the Transportation Research Board, No. 1925.* TRB, National Research Council, Washington, D.C., 2005, pp. 48-57.

13. Cassidy, M. J. and R. L. Bertini. Some Traffic Features at Freeway Bottlenecks. *Transportation Research Part B: Methodological*. Elsevier Science Ltd. Vol. 33B, No. 1, January 1999, pp. 25-42.

14. Dowling Associates. *Low-Cost Improvements for Recurring Freeway Bottlenecks.* Interim Report, NCHRP 3-83. TRB, Washington, D.C., December 2006.

15. Chen, C., A. Skabardonis, and P. Varaiya. Systematic Identification of Freeway Bottlenecks. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1867.* TRB, National Research Council, Washington, D.C., 2004, pp. 46-52.

16. Dowling and Associates. *Low-Cost Improvements for Recurring Freeway Bottlenecks.* NCHRP 3-83 Research Plan Proposal. April, 2005.

17. Brilon, W., J. Geistefeldt, and H. Zurlinden. Implementing the Concept of Reliability for Highway Capacity Analysis. Transportation Research Board 86th Annual Meeting 2007, Paper 07-2953. Washington, D.C., 2007.

18. Gomes, G., A. May, and R. Horowitz. Congested Freeway Microsimulation Model Using VISSIM. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1876*, TRB, National Research Council, Washington, D.C., 2004, pp. 71-81.

19. *Highway Capacity Manual: HCM 2000*. Transportation Research Board, National Research Council, Washington, D.C., 2000.

20. *Status of the Nation's Highways, Bridges, and Transit: 2004 Conditions and Performance*. Federal Highway Administration, United States Department of Transportation. Washington, D.C., 2006

21. Bloomberg, L. and J. Dale. Comparison of VISSIM and CORSIM Traffic Simulation Models on a Congested Network. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1727*. TRB, National Research Council, Washington, D. C., 2000, pp. 52-60.

22. Eads, Brian. MS Thesis Defense. North Carolina State University,

23. Hall, F. L., L. Bloomberg, N. M. Rouphail, B. Eads, and A. D. May. Validation Results for Four Models of Oversaturated Freeway Facilities. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1710*. TRB, National Research Council, Washington, D.C., 2000, pp. 161-170.

24. *TSIS User's Guide*. ITT Industries, Inc. Colorado Springs, CO, 2003.

25. UCI Testbed Micro-simulation Lab. Center of Traffic Simulation Studies at University of California Irvine. http://www.its.ucs.edu/ctss/sim_models/vissim.html. Accessed 06/21/2006.

26. *VISSIM 4.10 User Manual*. Planung Transport Verkehr (PTV) AG. Germany 2005.

27. Xin, W. Wuping Xin Homepage. http://www.tc.umn.edu/~xinxx007/html/gallery_fset.html. Accessed 7/27/2007.

28. Dale, J. *Re: 4.10 – Temporary Lane Closure*. E-mail Correspondence. 5/10/2007, 1:10PM EST.

29. *VISSIM 4.20 User Manual.* Planung Transport Verkehr (PTV) AG. Germany 2006.

30. Harris, Jim. Telephone Conversation. July 2, 2007.

31. *I-44/I-270 Interchange Traffic Study Saint Louis County Missouri: Technical Memorandum.* Crawford, Bunte, Brammeier. Prepared for the Missouri Department of Transportation. December 19, 2003.

32. Aronsson, K. F. M. *Speed Characteristics of Urban Streets Based on Driver Behavior Studies and Simulation.* Doctoral Thesis in Infrastructure, Royal Institute of Technology (KTH) School of Architecture and the Built Environment, Stockholm, Sweded, 2006.

33. *A Policy on Geometric Design of Highways and Streets*. 4th edition. American Association of State Highway and Transportation Officials, Washington, D.C., 2001.

APPENDIX A

Simulation Model Inputs

Missouri Site Origin-Demand (vph) Matrix

NB I-270
Time Periods 1, 2, 7, & 8

	Destinations				
Origins	**1**	**2**	**3**	**4**	**Sum**
1	977	775	406	3400	**5558**
2	0	296	154	929	**1379**
3	0	0	0	1701	**1701**
4	0	0	0	581	**581**
Sum	**977**	**1071**	**560**	**6611**	

NB I-270
Time Periods 3, 4, 5, & 6

	Destinations				
Origins	**1**	**2**	**3**	**4**	**Sum**
1	1465	1162	604	5106	**8337**
2	0	430	229	1347	**2006**
3	0	0	0	2552	**2552**
4	0	0	0	872	**872**
Sum	**1465**	**1592**	**833**	**9877**	

SB I-270
Time Periods 1, 2, 7, &8

	Destinations					
Origins	**1**	**2**	**3**	**4**	**5**	**Sum**
1	263	1271	1330	373	956	**4193**
2	0	0	0	341	884	**1225**
3	0	0	0	0	756	**756**
Sum	**263**	**1271**	**1330**	**714**	**2596**	

SB I-270
Time Periods 3, 4, 5, & 6

	Destinations					
Origins	**1**	**2**	**3**	**4**	**5**	**Sum**
1	394	1906	1995	556	1439	**6290**
2	0	0	0	515	1323	**1838**
3	0	0	0	0	1094	**1094**
Sum	**394**	**1906**	**1995**	**1071**	**3856**	

EB I-44
Time Periods 1, 2, 7, & 8

	Destinations					
Origins	**1**	**2**	**3**	**4**	**5**	**Sum**
1	525	645	137	151	1692	**3150**
2	0	188	21	22	392	**623**
3	0	280	49	50	493	**872**
4	0	0	0	60	917	**977**
5	0	0	0	235	591	**826**
6	0	0	0	0	662	**662**
Sum	**525**	**1113**	**207**	**518**	**4747**	

EB I-44
Time Periods 3, 4, 5, & 6

	Destinations					
Origins	**1**	**2**	**3**	**4**	**5**	**Sum**
1	788	966	205	226	2540	**4725**
2	0	284	28	31	592	**935**
3	0	420	77	78	733	**1308**
4	0	0	0	90	1375	**1465**
5	0	0	0	349	879	**1228**
6	0	0	0	0	992	**992**
Sum	**788**	**1670**	**310**	**774**	**7111**	

WB I-44
Time Periods 1, 2, 7, &8

	Destinations					
Origins	**1**	**2**	**3**	**4**	**5**	**Sum**
1	413	1194	469	0	329	**2405**
2	0	175	30	31	37	**273**
3	0	0	114	79	122	**315**
4	0	0	553	531	747	**1831**
5	0	0	0	0	245	**245**
Sum	**413**	**1369**	**1166**	**641**	**1480**	

WB I-44
Time Periods 3, 4, 5, & 6

	Destinations					
Origins	**1**	**2**	**3**	**4**	**5**	**Sum**
1	620	1790	714	0	483	**3607**
2	0	262	42	42	63	**409**
3	0	0	163	116	194	**473**
4	0	0	827	801	1110	**2738**
5	0	0	0	0	368	**368**
Sum	**620**	**2052**	**1746**	**959**	**2218**	

Wisconsin Site Origin-Demand (vph) Matrices

Period 1 **Destinations**

Origins	1	2	3	4	5	6	7	8	9	10	11	12	13	Sum
1	60	53	126	100	137	45	307	46	49	39	111	79	201	1355
2	67	59	140	111	152	50	341	52	55	43	123	88	223	1504
3	0	10	24	19	26	9	60	9	10	8	21	15	39	251
4	0	0	14	11	15	5	34	5	6	4	12	9	22	139
5	0	0	0	29	40	13	90	14	14	11	32	23	59	325
6	0	0	0	0	26	9	58	9	9	7	21	15	38	192
7	0	0	0	0	0	0	124	19	20	16	45	32	82	337
8	0	0	0	0	0	0	0	75	79	62	178	127	323	844
9	0	0	0	0	0	0	0	0	15	11	33	23	59	142
10	0	0	0	0	0	0	0	0	29	23	64	46	117	278
11	0	0	0	0	0	0	0	0	0	18	51	36	92	197
12	0	0	0	0	0	0	0	0	0	31	88	63	161	343
13	0	0	0	0	0	0	0	0	0	0	43	31	78	151
14	0	0	0	0	0	0	0	0	0	0	33	23	60	116
Sum	127	122	304	271	**396**	130	1015	228	285	274	856	611	1554	**6173**

Period 2 **Destinations**

Origins	1	2	3	4	5	6	7	8	9	10	11	12	13	Sum
1	68	60	143	113	155	51	348	53	56	44	126	90	228	1534
2	76	66	159	126	172	57	386	58	62	49	139	100	253	1703
3	0	12	28	22	30	10	67	10	11	9	24	17	44	284
4	0	0	16	13	17	6	39	6	6	5	14	10	25	157
5	0	0	0	33	45	15	102	15	16	13	37	26	67	368
6	0	0	0	0	29	10	66	10	11	8	24	17	43	217
7	0	0	0	0	0	0	141	21	23	18	51	36	92	382
8	0	0	0	0	0	0	0	84	90	71	201	144	366	956
9	0	0	0	0	0	0	0	0	16	13	37	26	67	160
10	0	0	0	0	0	0	0	0	32	25	73	52	132	314
11	0	0	0	0	0	0	0	0	0	20	57	41	104	223
12	0	0	0	0	0	0	0	0	0	35	100	72	182	389
13	0	0	0	0	0	0	0	0	0	0	49	35	88	172
14	0	0	0	0	0	0	0	0	0	0	37	27	68	132
Sum	144	138	345	307	**449**	147	1149	258	323	310	969	692	1760	**6992**

Period 3 **Destinations**

Origins	1	2	3	4	5	6	7	8	9	10	11	12	13	Sum
1	97	85	202	161	220	72	494	75	79	62	178	127	323	2175
2	108	94	225	179	244	80	548	83	88	69	198	141	359	2415
3	0	16	39	31	43	14	96	14	15	12	34	25	63	403
4	0	0	23	18	25	8	55	8	9	7	20	14	36	223
5	0	0	0	47	64	21	144	22	23	18	52	37	94	522
6	0	0	0	0	42	14	93	14	15	12	34	24	61	308
7	0	0	0	0	0	0	200	30	32	25	72	51	131	542
8	0	0	0	0	0	0	0	120	127	100	286	204	518	1355
9	0	0	0	0	0	0	0	0	23	18	53	38	95	227
10	0	0	0	0	0	0	0	0	46	36	103	74	187	446
11	0	0	0	0	0	0	0	0	0	29	81	58	148	316
12	0	0	0	0	0	0	0	0	0	50	142	101	258	551
13	0	0	0	0	0	0	0	0	0	0	69	49	125	243
14	0	0	0	0	0	0	0	0	0	0	53	38	96	186
Sum	204	196	489	436	**636**	209	1629	366	458	439	1374	982	2495	**9914**

Period 4 **Destinations**

Origins	1	2	3	4	5	6	7	8	9	10	11	12	13	Sum
1	118	104	247	196	268	88	602	91	97	76	217	155	394	2655
2	131	115	274	218	298	98	669	101	107	85	241	172	438	2947
3	0	20	48	38	52	17	117	18	19	15	42	30	76	491
4	0	0	28	22	30	10	67	10	11	9	24	17	44	272
5	0	0	0	57	78	26	176	27	28	22	63	45	115	638
6	0	0	0	0	51	17	114	17	18	14	41	29	75	376
7	0	0	0	0	0	0	244	37	39	31	88	63	160	661
8	0	0	0	0	0	0	0	146	155	122	348	249	633	1653
9	0	0	0	0	0	0	0	0	29	22	64	46	116	277
10	0	0	0	0	0	0	0	0	56	44	126	90	228	544
11	0	0	0	0	0	0	0	0	0	35	99	71	181	386
12	0	0	0	0	0	0	0	0	0	61	173	124	315	673
13	0	0	0	0	0	0	0	0	0	0	84	60	153	297
14	0	0	0	0	0	0	0	0	0	0	64	46	117	228
Sum	250	239	597	532	**776**	255	1988	447	559	536	1677	1198	3045	**12098**

Period 5 **Destinations**

Origins	1	2	3	4	5	6	7	8	9	10	11	12	13	Sum
1	105	92	219	174	238	78	535	81	86	68	193	138	350	2358
2	117	102	244	194	264	87	594	90	95	75	214	153	389	2617
3	0	18	42	34	46	15	104	16	17	13	37	27	68	436
4	0	0	25	19	27	9	60	9	10	8	22	15	39	241
5	0	0	0	51	69	23	156	24	25	20	56	40	102	566
6	0	0	0	0	45	15	101	15	16	13	36	26	66	334
7	0	0	0	0	0	0	217	33	35	27	78	56	142	587
8	0	0	0	0	0	0	0	130	138	109	309	221	562	1468
9	0	0	0	0	0	0	0	0	25	20	57	41	103	246
10	0	0	0	0	0	0	0	0	50	39	112	80	203	483
11	0	0	0	0	0	0	0	0	0	31	88	63	160	343
12	0	0	0	0	0	0	0	0	0	54	154	110	280	597
13	0	0	0	0	0	0	0	0	0	0	75	53	136	264
14	0	0	0	0	0	0	0	0	0	0	57	41	104	202
Sum	222	212	530	472	**689**	227	1766	397	496	476	1489	1064	2704	**10744**

Period 6 **Destinations**

Origins	1	2	3	4	5	6	7	8	9	10	11	12	13	Sum
1	101	89	211	168	229	75	515	78	83	65	186	133	337	2269
2	112	98	234	186	254	84	572	86	92	72	206	147	374	2519
3	0	17	41	33	44	15	100	15	16	13	36	26	65	420
4	0	0	24	19	26	8	58	9	9	7	21	15	38	232
5	0	0	0	49	67	22	150	23	24	19	54	39	98	545
6	0	0	0	0	43	14	97	15	16	12	35	25	64	322
7	0	0	0	0	0	0	208	32	33	26	75	54	137	565
8	0	0	0	0	0	0	0	125	133	104	298	213	541	1413
9	0	0	0	0	0	0	0	0	24	19	55	39	100	237
10	0	0	0	0	0	0	0	0	48	38	108	77	195	465
11	0	0	0	0	0	0	0	0	0	30	85	61	154	330
12	0	0	0	0	0	0	0	0	0	52	148	106	269	575
13	0	0	0	0	0	0	0	0	0	0	72	51	131	254
14	0	0	0	0	0	0	0	0	0	0	55	39	100	195
Sum	213	204	510	454	**664**	218	1700	382	478	458	1433	1024	2603	**10341**

Period 7	**Destinations**													
Origins	1	2	3	4	5	6	7	8	9	10	11	12	13	Sum
1	120	105	250	199	271	89	610	92	98	77	220	157	400	2689
2	133	116	278	221	301	99	677	102	109	86	244	174	444	2985
3	0	20	48	39	53	17	118	18	19	15	43	30	77	497
4	0	0	28	22	30	10	68	10	11	9	25	18	45	275
5	0	0	0	58	79	26	178	27	29	23	64	46	117	646
6	0	0	0	0	51	17	115	17	19	15	42	30	76	381
7	0	0	0	0	0	0	247	37	40	31	89	64	162	670
8	0	0	0	0	0	0	0	148	157	124	353	252	641	1675
9	0	0	0	0	0	0	0	0	29	23	65	46	118	281
10	0	0	0	0	0	0	0	0	57	45	127	91	231	551
11	0	0	0	0	0	0	0	0	0	35	101	72	183	391
12	0	0	0	0	0	0	0	0	0	62	176	125	319	681
13	0	0	0	0	0	0	0	0	0	0	85	61	155	301
14	0	0	0	0	0	0	0	0	0	0	65	47	119	230
Sum	253	242	604	538	**786**	258	2014	452	566	543	1698	1213	3084	**12253**

Period 8	**Destinations**													
Origins	1	2	3	4	5	6	7	8	9	10	11	12	13	Sum
1	116	101	242	192	262	86	589	89	95	75	213	152	386	2597
2	128	113	268	213	291	96	654	99	105	83	236	169	429	2883
3	0	20	47	37	51	17	114	17	18	14	41	29	75	481
4	0	0	27	21	29	10	66	10	11	8	24	17	43	266
5	0	0	0	56	76	25	172	26	28	22	62	44	113	624
6	0	0	0	0	50	16	111	17	18	14	40	29	73	368
7	0	0	0	0	0	0	239	36	38	30	86	61	156	647
8	0	0	0	0	0	0	0	143	152	120	341	244	619	1618
9	0	0	0	0	0	0	0	0	28	22	63	45	114	271
10	0	0	0	0	0	0	0	0	55	43	123	88	223	532
11	0	0	0	0	0	0	0	0	0	34	97	69	177	378
12	0	0	0	0	0	0	0	0	0	59	170	121	308	658
13	0	0	0	0	0	0	0	0	0	0	82	59	149	290
14	0	0	0	0	0	0	0	0	0	0	63	45	115	223
Sum	244	234	584	520	**759**	250	1945	437	547	525	1641	1172	2979	**11836**

Period 9	**Destinations**													
Origins	1	2	3	4	5	6	7	8	9	10	11	12	13	Sum
1	92	81	192	153	209	69	469	71	75	59	169	121	307	2065
2	102	89	213	170	232	76	520	79	84	66	188	134	341	2293
3	0	16	37	30	40	13	91	14	15	11	33	23	59	382
4	0	0	21	17	23	8	52	8	8	7	19	13	34	211
5	0	0	0	45	61	20	137	21	22	17	49	35	90	496
6	0	0	0	0	39	13	89	13	14	11	32	23	58	293
7	0	0	0	0	0	0	190	29	30	24	68	49	124	515
8	0	0	0	0	0	0	0	114	121	95	271	194	492	1287
9	0	0	0	0	0	0	0	0	22	17	50	36	91	216
10	0	0	0	0	0	0	0	0	44	34	98	70	178	423
11	0	0	0	0	0	0	0	0	0	27	77	55	140	300
12	0	0	0	0	0	0	0	0	0	47	135	96	245	523
13	0	0	0	0	0	0	0	0	0	0	65	47	119	231
14	0	0	0	0	0	0	0	0	0	0	50	36	91	177
Sum	194	186	464	414	**604**	199	1547	347	435	417	1305	932	2369	**9413**

Period 10	**Destinations**													
Origins	1	2	3	4	5	6	7	8	9	10	11	12	13	Sum
1	76	67	159	126	172	57	387	59	62	49	140	100	254	1706
2	84	74	176	140	191	63	430	65	69	54	155	111	281	1894
3	0	13	31	24	33	11	75	11	12	9	27	19	49	316
4	0	0	18	14	19	6	43	7	7	5	16	11	28	175
5	0	0	0	37	50	17	113	17	18	14	41	29	74	410
6	0	0	0	0	33	11	73	11	12	9	26	19	48	242
7	0	0	0	0	0	0	157	24	25	20	57	40	103	425
8	0	0	0	0	0	0	0	94	100	79	224	160	407	1063
9	0	0	0	0	0	0	0	0	18	14	41	29	75	178
10	0	0	0	0	0	0	0	0	36	28	81	58	147	350
11	0	0	0	0	0	0	0	0	0	22	64	46	116	248
12	0	0	0	0	0	0	0	0	0	39	111	80	202	432
13	0	0	0	0	0	0	0	0	0	0	54	39	98	191
14	0	0	0	0	0	0	0	0	0	0	41	30	75	146
Sum	160	153	383	342	**499**	164	1278	287	359	345	1078	770	1957	**7775**

Period 11	**Destinations**													
Origins	1	2	3	4	5	6	7	8	9	10	11	12	13	Sum
1	75	66	156	124	169	56	381	58	61	48	137	98	249	1679
2	83	73	173	138	188	62	423	64	68	54	153	109	277	1864
3	0	13	30	24	33	11	74	11	12	9	27	19	48	311
4	0	0	17	14	19	6	43	6	7	5	15	11	28	172
5	0	0	0	36	49	16	111	17	18	14	40	29	73	403
6	0	0	0	0	32	11	72	11	12	9	26	19	47	238
7	0	0	0	0	0	0	154	23	25	20	56	40	101	418
8	0	0	0	0	0	0	0	92	98	77	220	157	400	1046
9	0	0	0	0	0	0	0	0	18	14	41	29	74	175
10	0	0	0	0	0	0	0	0	35	28	80	57	144	344
11	0	0	0	0	0	0	0	0	0	22	63	45	114	244
12	0	0	0	0	0	0	0	0	0	38	110	78	199	425
13	0	0	0	0	0	0	0	0	0	0	53	38	97	188
14	0	0	0	0	0	0	0	0	0	0	41	29	74	144
Sum	158	151	377	336	**491**	161	1257	282	353	339	1060	757	1925	**7650**

Period 12	**Destinations**													
Origins	1	2	3	4	5	6	7	8	9	10	11	12	13	Sum
1	67	59	140	112	152	50	342	52	55	43	123	88	224	1508
2	75	65	156	124	169	56	380	57	61	48	137	98	249	1675
3	0	11	27	22	29	10	66	10	11	8	24	17	43	279
4	0	0	16	12	17	6	38	6	6	5	14	10	25	154
5	0	0	0	33	44	15	100	15	16	13	36	26	65	362
6	0	0	0	0	29	9	65	10	10	8	23	17	42	214
7	0	0	0	0	0	0	139	21	22	18	50	36	91	376
8	0	0	0	0	0	0	0	83	88	69	198	141	360	939
9	0	0	0	0	0	0	0	0	16	13	36	26	66	158
10	0	0	0	0	0	0	0	0	32	25	71	51	130	309
11	0	0	0	0	0	0	0	0	0	20	56	40	103	219
12	0	0	0	0	0	0	0	0	0	35	98	70	179	382
13	0	0	0	0	0	0	0	0	0	0	48	34	87	169
14	0	0	0	0	0	0	0	0	0	0	37	26	67	129
Sum	142	136	339	302	**441**	145	1130	254	318	305	953	681	1730	**6874**

Wiedmann 99 Car Following Parameters

VISSIM Parameter	Default	St. Louis, MO	Milwaukee, WI
CC0	4.92 ft	4.92 ft	5.58 ft
CC1	0.9 s	0.9 s	0.9 s
CC4	-0.35	-0.35	-2.0
CC5	0.35	0.35	2.0

Parameters not explicitly noted in the table are at the default setting

Lane Change Parameters

VISSIM Parameter	Default	St. Louis, MO	Milwaukee, WI
Own Maximum Deceleration	-13.12 ft/s^2	-9.84 ft/s^2	-13.12 ft/s^2
Own -1ft/s^2 per distance	200 ft	100 ft	200 ft
Trailing Vehicle -1 ft/s^2 per distance	200 ft	100 ft	200 ft
Safety distance reduction factor	0.60	0.10	0.10
Maximum Deceleration for cooperative braking	-9.84 ft/s^2	-29.53 ft/s^2	-29.53 ft/s^2

Parameters not explicitly noted in the table are at the default setting

Milwaukee, Wisconsin Ramp Meter Timings

On-Ramp	VISSIM Metered Flow (vph)	FREEVAL Metered Flow (vph)
Northbound 27th St.	**514***	**460**
Southbound 27th St.	**240**	**239**
Loomis Rd.	**600**	**566**
60th St.	**360**	**346**
84th St.	**600***	**609**
Beloit Rd.	**257**	**244**
Oklahoma Ave.	**514**	**505**
National Ave.	**360**	**348**
Lincoln Ave.	**600***	**620**
Eastbound Greenfield Ave.	**276**	**261**
Westbound Greenfield Ave.	**212**	**204**

Trucks are not required to stop at meter

Note: Ramp meters are on from simulation seconds 1800-9000 (time periods 3 through 10).

St. Louis, Missouri Ramp Meter Timing

Ramp	VISSIM Metered Flow (vph)	FREEVAL Metered Flow (vph)
South Highway Drive (On)	**900**	**1350**
Rudder Road (On)	**450**	
Big Bend Rd. (On)	**900**	**900**
Watson Rd. (C/D)	**600 (× 2)**	**N/A**
WB I-44 Segment 4 Off-Ramp (Off)	**1010 (× 2)***	**N/A**
Gravois Rd. (On)	**723 (× 2)***	**1448**
NB I-270 Segment 10 On-Ramp	**N/A**	**2444****

Meters were modeled as reduced speed zones to force a specific amount of delay.

*****This is the effective metering rate created if actual meters were placed on the Watson Rd., Rudder R., South Highway Dr., and the WB I-44 Off-Ramp that feed into this on-ramp.***

APPENDIX B

Simulation Model Outputs

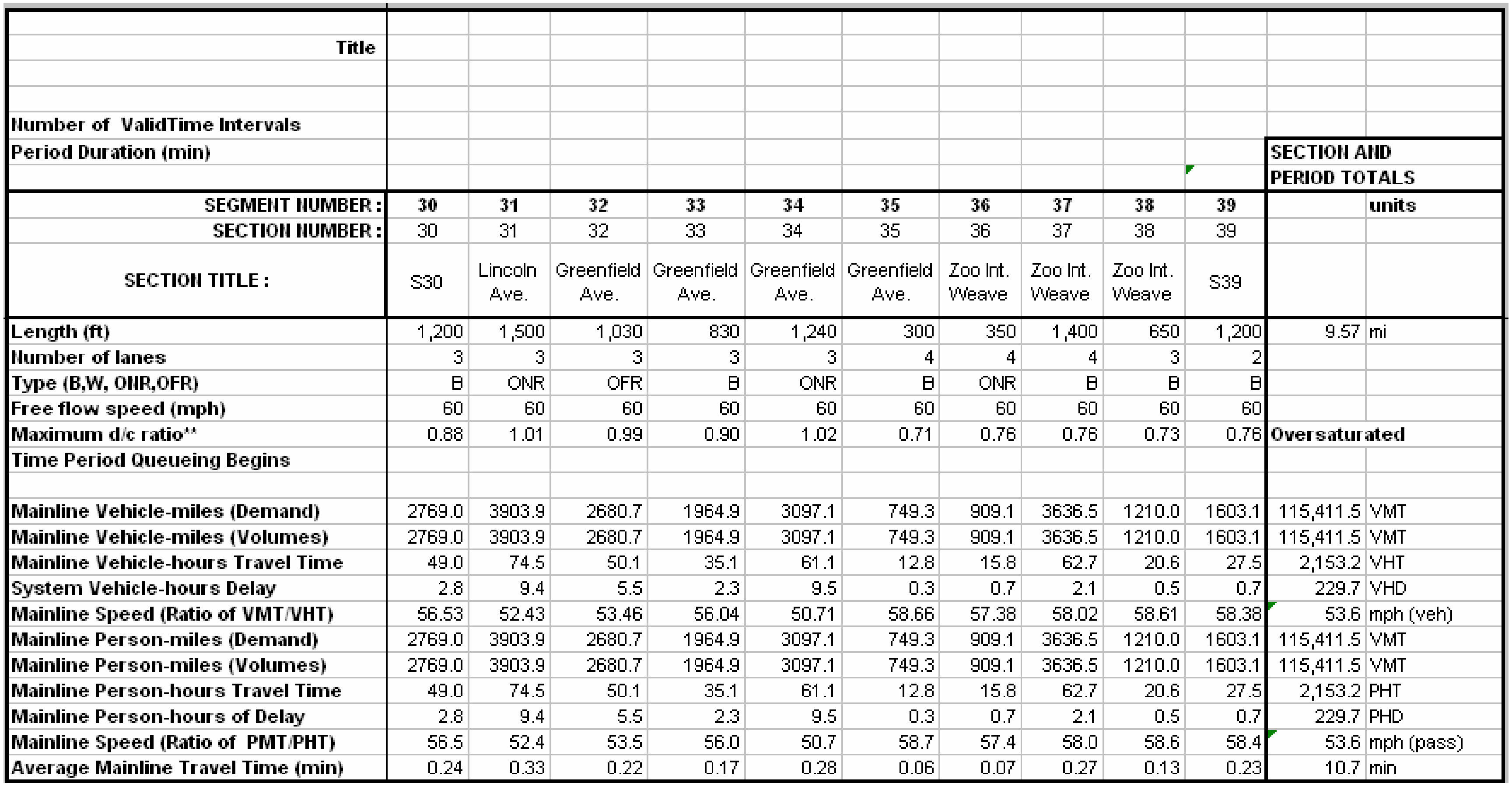
Sample FREEVAL Summary Output

Title **Freeway Name**

Number of ValidTime Intervals 8
Period Duration (min) 120

SEGMENT NUMBER :	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**SECTION AND PERIOD TOTALS**	**units**
SECTION NUMBER :	1	2	3	4	5	6	7	8	9	10	11	12	13		
SECTION TITLE :	S01	S02	S03	S04	S05	S06	S07	S08	S09	S10	S11	S12	S13		
Length (ft)	4,862	1,500	3,141	1,500	4,912	1,933	278	1,500	1,291	1,500	1,026	4,911	1,126	5.59	mi
Number of lanes	5	5	4	5	5	5	5	5	4	5	5	4	4		
Type (B,W, ONR,OFR)	B	B	B	B	B	OFR	B	B	B	B	B	B	ONR		
Free flow speed (mph)	62	62	62	62	62	62	62	62	62	62	62	62	62		
Maximum d/c ratio**	0.74	0.74	0.76	0.79	0.79	0.79	0.65	0.65	0.72	0.80	0.80	1.00	1.10	**Oversaturated**	
Time Period Queueing Begins								6	4	3	3	3			
Mainline Vehicle-miles (Demand)	12738.3	3930.0	6783.3	4196.7	13742.8	5408.2	638.2	3443.5	2624.7	4252.5	2908.7	13922.7	3500.7	78,090.3	VMT
Mainline Vehicle-miles (Volumes)	12738.3	3930.0	6783.3	4174.6	13670.5	5379.7	633.3	3417.1	2587.1	4212.5	2881.4	13789.2	3456.0	77,653.1	VMT
Mainline Vehicle-hours Travel Time	204.6	63.1	109.1	67.3	220.2	88.6	10.2	55.1	53.1	126.4	107.1	314.3	64.9	1,484.0	VHT
System Vehicle-hours Delay	0.1	0.0	0.2	0.2	0.8	2.3	0.0	0.3	11.5	265.0	60.9	92.9	9.4	443.7	VHD
Mainline Speed (Ratio of VMT/VHT)	62.26	62.26	62.19	62.08	62.08	60.70	62.03	62.00	48.76	33.32	26.89	43.88	53.28	52.3	mph (veh)
Mainline Person-miles (Demand)	12738.3	3930.0	6783.3	4196.7	13742.8	5408.2	638.2	3443.5	2624.7	4252.5	2908.7	13922.7	3500.7	78,090.3	VMT
Mainline Person-miles (Volumes)	12738.3	3930.0	6783.3	4174.6	13670.5	5379.7	633.3	3417.1	2587.1	4212.5	2881.4	13789.2	3456.0	77,653.1	VMT
Mainline Person-hours Travel Time	204.6	63.1	109.1	67.3	220.2	88.6	10.2	55.1	53.1	126.4	107.1	314.3	64.9	1,484.0	PHT
Mainline Person-hours of Delay	0.1	0.0	0.2	0.2	0.8	2.3	0.0	0.3	11.5	265.0	60.9	92.9	9.4	443.7	PHD
Mainline Speed (Ratio of PMT/PHT)	62.3	62.3	62.2	62.1	62.1	60.7	62.0	62.0	48.8	33.3	26.9	43.9	53.3	52.3	mph (pass)
Average Mainline Travel Time (min)	0.89	0.27	0.57	0.27	0.90	0.36	0.05	0.28	0.30	0.51	0.43	1.27	0.24	6.4	min

Sample FREEVAL Summary Output Showing Hidden Bottlenecks in Segments 31 and 34



Title												
Number of ValidTime Intervals												
Period Duration (min)											**SECTION AND**	
											PERIOD TOTALS	
SEGMENT NUMBER :	**30**	**31**	**32**	**33**	**34**	**35**	**36**	**37**	**38**	**39**		**units**
SECTION NUMBER :	30	31	32	33	34	35	36	37	38	39		
SECTION TITLE :	S30	Lincoln Ave.	Greenfield Ave.	Greenfield Ave.	Greenfield Ave.	Greenfield Ave.	Zoo Int. Weave	Zoo Int. Weave	Zoo Int. Weave	S39		
Length (ft)	1,200	1,500	1,030	830	1,240	300	350	1,400	650	1,200	9.57	mi
Number of lanes	3	3	3	3	3	4	4	4	3	2		
Type (B,W, ONR,OFR)	B	ONR	OFR	B	ONR	B	ONR	B	B	B		
Free flow speed (mph)	60	60	60	60	60	60	60	60	60	60		
Maximum d/c ratio**	0.88	1.01	0.99	0.90	1.02	0.71	0.76	0.76	0.73	0.76	**Oversaturated**	
Time Period Queueing Begins												
Mainline Vehicle-miles (Demand)	2769.0	3903.9	2680.7	1964.9	3097.1	749.3	909.1	3636.5	1210.0	1603.1	115,411.5	VMT
Mainline Vehicle-miles (Volumes)	2769.0	3903.9	2680.7	1964.9	3097.1	749.3	909.1	3636.5	1210.0	1603.1	115,411.5	VMT
Mainline Vehicle-hours Travel Time	49.0	74.5	50.1	35.1	61.1	12.8	15.8	62.7	20.6	27.5	2,153.2	VHT
System Vehicle-hours Delay	2.8	9.4	5.5	2.3	9.5	0.3	0.7	2.1	0.5	0.7	229.7	VHD
Mainline Speed (Ratio of VMT/VHT)	56.53	52.43	53.46	56.04	50.71	58.66	57.38	58.02	58.61	58.38	53.6	mph (veh)
Mainline Person-miles (Demand)	2769.0	3903.9	2680.7	1964.9	3097.1	749.3	909.1	3636.5	1210.0	1603.1	115,411.5	VMT
Mainline Person-miles (Volumes)	2769.0	3903.9	2680.7	1964.9	3097.1	749.3	909.1	3636.5	1210.0	1603.1	115,411.5	VMT
Mainline Person-hours Travel Time	49.0	74.5	50.1	35.1	61.1	12.8	15.8	62.7	20.6	27.5	2,153.2	PHT
Mainline Person-hours of Delay	2.8	9.4	5.5	2.3	9.5	0.3	0.7	2.1	0.5	0.7	229.7	PHD
Mainline Speed (Ratio of PMT/PHT)	56.5	52.4	53.5	56.0	50.7	58.7	57.4	58.0	58.6	58.4	53.6	mph (pass)
Average Mainline Travel Time (min)	0.24	0.33	0.22	0.17	0.28	0.06	0.07	0.27	0.13	0.23	10.7	min

Sample VISSIM Output

```
Link Evaluation

File:
s:\zacharyclarkdata\modeling_3_83\wi\vissim\wi_894_baseline_gomes.inp
Comment:  Random Seed = 5
Date:     Monday, August 06, 2007 9:08:30 PM

Vehicle Class: 0 = All Vehicle Types
Vehicle Class: 10 = Car
Vehicle Class: 20 = HGV
Vehicle Class: 30 = Bus
Vehicle Class: 40 = Tram
Vehicle Class: 50 = Pedestrian
Vehicle Class: 60 = Bike


Density: Vehicle density [veh/mi] (Vehicle Class 0)
Lane: Lane Number
Link: Link Number
LostT: Relative lost time [s/s] (Vehicle Class 0)
SegLen: Segment length [ft]
v: Average speed [mph] (Vehicle Class 0)
Volume: Volume [veh/h] (Vehicle Class 0)

Density(0); Lane;  Link; LostT(0); SegLen;     v(0); Volume(0);
    13.94;    1;     1;   0.02; 2118.5;    55.37;   771.72;
    12.96;    2;     1;   0.01; 2118.5;    55.41;   718.42;
     5.22;    1;     2;   0.01; 1234.3;    59.70;   311.45;
    17.75;    2;     2;   0.04; 1234.3;    57.98;  1028.98;
     1.34;    1;     3;   0.00; 2015.2;    59.80;    79.83;
    18.90;    2;     3;   0.02; 2015.2;    58.47;  1105.25;
    14.45;    3;     3;   0.02; 2015.2;    59.33;   857.28;
    11.97;    4;     3;   0.01; 2015.2;    59.60;   713.63;
     3.14;    1;     4;   0.01;  298.0;    39.75;   124.87;
     2.71;    2;     4;   0.00;  298.0;    43.55;   117.97;
     1.14;    3;     4;   0.00;  298.0;    45.32;    51.83;
     1.84;    1;     5;   0.07; 1054.9;    45.60;    84.01;
     1.23;    1;     6;   0.00;  180.5;    44.48;    54.78;
     2.28;    2;     6;   0.00;  180.5;    44.60;   101.90;
     1.06;    3;     6;   0.00;  180.5;    44.44;    47.22;
     9.27;    1;     7;   0.02;  905.4;    28.42;   263.39;
     6.37;    1;     8;   0.12;  597.1;    40.11;   255.43;
     3.60;    2;     8;   0.02;  597.1;    44.33;   159.41;
     1.53;    3;     8;   0.00;  597.1;    45.50;    69.82;
     3.94;    1;     9;   0.06;  529.5;    42.29;   166.43;
     1.67;    2;     9;   0.01;  529.5;    45.39;    75.69;
     0.55;    3;     9;   0.00;  529.5;    45.76;    25.30;
     3.73;    1;    10;   0.02;  501.4;    39.23;   146.48;
     2.13;    2;    10;   0.02;  501.4;    42.85;    91.45;
```

APPENDIX C

Working Paper on Enhancements to the FREEVAL Model

NCHRP 3-83
Low Cost Improvements for Recurring Freeway Bottlenecks

Task 7D. Working Paper on Enhancements to the FREEVAL Model

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1.0 Introduction

This working paper is intended to provide recommendations for improving and extending various computational and reporting features of the FREEVAL (**FREE**way **EVAL**uation) model, as proposed in the original NCHRP 3-83 proposal Task 7D [1]. The proposed recommendations have emerged on the basis of extensive model runs carried out by the project team for two, real-world, complex freeway facilities on I-270/I-44 in the St. Louis, Missouri and I-90/I-94 in the Milwaukee, Wisconsin metro areas. Results of these analyses are reported elsewhere in the project quarterly reports.

Additional input was obtained in May 2007, when the NC State team presented a Webinar on FREEVAL at the FHWA Turner-Fairbanks Highway Research Center. Several staff members from the FHWA Office of Operations participated and provided very useful comments on the capabilities, potential enhancements to and future applications of the model. The working paper is organized as follows. First, a brief summary of FREEVAL capabilities, as is stands today, is provided. This is followed by a section of proposed improvements organized in four general areas: (a) changes in the underlying algorithms to improve or extend FREEVAL usability; (b) enabling data entry of site-specific characteristics that may be different that the HCM default values, (c) addition of a decision support tool to enable the user to select the most cost-effective bottleneck mitigation measures and their sequence, based on site-specific characteristics; (d) streamline the current FREEVAL output reports to provide summary reports that are bottleneck-specific (similar to the output that the PEMS real-time system now produces in Southern California); and (e) correct errors in units, formatting and other stylistic changes to make the program more user friendly. The paper concludes with proposed priorities and rough impacts associated with the various projects.

2.0 FREEVAL Current Status

FREEVAL was originally developed and conceived as a “computational engine” of the then new HCM2000 analysis chapter on directional freeway facilities. The detailed computational procedure underlying the analysis can be found in the Appendix of Chapter 22 in the HCM [2]. Model details and its measures of performance were compared to selected macro and micro-simulation models at six oversaturated freeway facilities and documented in several publications [3, 4, 5]. In contrast to the typical HCM analysis paradigm, which focuses on isolated segment and intersection analyses mostly for under-capacity conditions, FREEVAL deals with a facility as a series of connected freeway segments of various types (Basic, On-Ramp, etc.) over multiple periods.

2.1 Principal Features of FREEVAL

1. FREEVAL uses a macroscopic modeling approach– which is not as data and input coding intensive as for micro-simulation models
2. FREEVAL applies a systems approach in the facility analysis, recognizing traffic interaction between contiguous freeway segments.
3. FREEVAL can accept time varying traffic demands over multiple time intervals and explicitly considers the traffic interactions over such intervals, particularly in congested conditions where demand may need to be serviced in subsequent time periods.
4. FREEVAL explicitly models the effect of over-saturation and the presence of bottlenecks (both active and hidden), when a segment has demand to capacity d/c ration > 1.0. FREEVAL will report multiple congestion statistics beyond just the reporting of LOS F.
5. Both queue formation and dissipation in the vicinity of bottlenecks are explicitly considered. To be consistent with traffic flow concepts, a queue in FREEVAL is defined as any flow regime that has a density that exceeds the optimal density (at capacity) for the segment. Naturally, this implies that moving queues / platoons are accounted for in the model.
6. Bottleneck metering effects are explicitly accounted for while they are active. The metered flows are released and added to demand when either the demand drop or capacity increases in subsequent time periods.
7. FREEVAL can model *temporary* reductions (or increases) in capacity that emulated the effect of incidents and/or short term work zones. The severity of an incident is modeled trough the use of a capacity adjustment factor, or a reduction in the number of travel lanes. The duration of an incident is limited to an integer number of time intervals.
8. The FREEVAL code was originally written using metric units, per the then sponsor’s request. It can accept input and produce output in English units if desired, but this is done through soft conversions that might produce slightly different results that the HCM US unit method due to rounding, etc.

2.2 Principal Limitations / Restrictions in FREEVAL

1. The model was originally conceived as a tool for HCM level of service (LOS) analysis of directional freeway facilities, not as a bottleneck-identification and mitigation support tool. While in its current form FREEVAL produces useful

output for the latter purpose, it can and should be streamlined to provide easily accessible and understandable summary information on bottleneck impacts and the effect of mitigation measures on those impacts system-wide.

2. The model can currently handle freeway facilities of about 10-20 mi in length; this restriction ensures that flows doe not appreciably change during the time it takes for a vehicle to travel at the free flow speed.
3. There is a current limitation of 50 segments. A segment is defined consistent with the Highway Capacity Manual freeway analysis chapters.
4. There is a current limitation of simulating twelve time intervals in which traffic demand rates are allowed to change. The size of each interval may vary from 5 minutes to one hour.
5. FREEVAL does not perform lane-by-lane analysis, and therefore does not enable the analysis of dedicated HOV lanes, truck lanes, or truck restrictions.
6. Time-dependent demand flow rates must be entered in FREEVAL. This is required since real-time count data imported from freeway detection systems reflect volumes or flows, rather than demand. This limitation is not critical if flows do not exceed capacity, but could produce misleading results in the event of excessive queuing on the facility.
7. FREEVAL does not model the on-ramp roadway proper. It uses a simple input-output approach to accumulate queues and delays at the on-ramp gore point, assuming vertical queuing. Thus, queues that may spillback onto the surface street are not accounted for, although delays at the on-ramp are.
8. An important limitation of FREEVAL is that it does not consider capacity limits that may arise at the downstream end of an off-ramp due to ramp geometry or the presence of a signal or a stop sign. Thus, queues that may back up onto the freeway mainline at those locations are not accounted for.
9. While FREEVAL can model the effect of many bottleneck mitigation measures (such as auxiliary lanes, ramp metering, narrow lanes, shoulder use during the peak, etc.) their effect on segment capacity must be estimated or calibrated by the user. The only mechanism to do so at this time is through a capacity adjustment factor with the HCM2000 segment capacity used as the baseline. Capacity values cannot be obtained until an initial run with no capacity adjustment is made.
10. FREEVAL (like most micro-simulation models) is a freeway traffic impact analysis, not a decision support tool. As such, it can analyze the effect of bottleneck mitigation measures, but cannot recommend or prioritize which of the measures to select and in what sequence.
11. FREEVAL was designed as a supporting computational engine for an HCM chapter, and therefore is not as user friendly, or thoroughly documented, as commercial quality software, although it is fully programmed in Excel.

3.0 Proposed FREEVAL Enhancements:

The proposed enhancements are grouped into 5 different classes, each of which is described in detail in the next few sections. These classes of enhancements include:

A. Improve the underlying algorithms
B. Enable the use of field calibrated input data
C. Add a bottleneck mitigation decision support tool
D. Streamline output to produce bottleneck-specific performance measures
E. Correct formatting errors and improve readability of current outputs

3.1 Improving some of the Underlying Algorithms (Class-A)

A.1. Off-Ramp Model Enhancement: Feedback received from users and FHWA staff indicates that allowing for a capacity restriction at off-ramps would greatly enhance the realism of the model. This will require an output restriction at each off-ramp (in terms of a maximum flow rate), which could then propagate onto the mainline, creating a bottleneck. Additional input data items in this case include the length and number of lanes at the off-ramp (i.e. queue storage potential), and a speed-flow-density relationship for the ramp roadway.

A.2 On-Ramp Model Enhancement: A new on-ramp algorithm, which uses shock wave theory to propagate the queues and delays on the ramp roadway, would also greatly improve the realism of the current model. The model enhancement would include the addition of on-ramp length and storage capacity. This would enable the inclusion of travel time on the ramp as part of the system travel time. In addition, such a model would provide more reliable delays and queues than the current input-output model does.

A.3 Bottleneck Queue Allocation to Mainline and On-ramp Roadway: When a bottleneck occurs just downstream of an on-ramp due to heavy ramp and mainline demand, the resulting upstream queue is partially allocated to the mainline segment and the ramp roadway. The current algorithm seems to be favoring mainline traffic at the expense of ramp flow, resulting in large on-ramp queues. Calibration of the proper distribution of throughput between the ramp and mainline traffic upstream of a bottleneck is a difficult measurement issue that nevertheless needs to be carried out to improve the model realism.

A.4 Capacity during Queue Discharge: In its current version, FREEVAL uses the same segment capacity value in both uninterrupted flow and breakdown regimes. Research has shown [6] that during the queue discharge period, the maximum flow is normally lower than the uninterrupted flow capacity, by a factor of 5-8% depending on the study. This enhancement consists of reducing the effected segment capacities, when there is a queue, and restoring it to the uninterrupted value after the queues have fully dissipated. Field calibrated capacities would also be used in the modes, as more fully described in section 3.2

A.5 Automated Estimation of Traffic Demands from Flow Measurements: This limitation applies to existing freeway facilities where traffic demands are extracted from loop or other detector types on the mainline and ramps. While this problem is minor with under-saturated conditions, demands and flows could vary significantly when queues are present and persist over time. Thus, the first and most important restriction in using FREEVAL (or for that matter any other macro or micro-simulation model) is to ensure that the pre-peak and post-peak periods are included into the model. Otherwise, there is no way of estimating demands from flows, or even guaranteeing that what was inputted is indeed traffic demand. By lengthening the analysis period, all demand is captured, although how it is distributed in each smaller time period remains a challenge. Currently, the HCM recommends the use of a flow adjustment factor based on summing all entry and exit flows during a time period, and the application of this factor facility-wide. An alternative, more robust algorithm that can accept input and output flow rates by period, and produces prediction of demand by time period should be considered.

3.2 Enabling Field Calibrated Parameters in FREEVAL (Class-B)

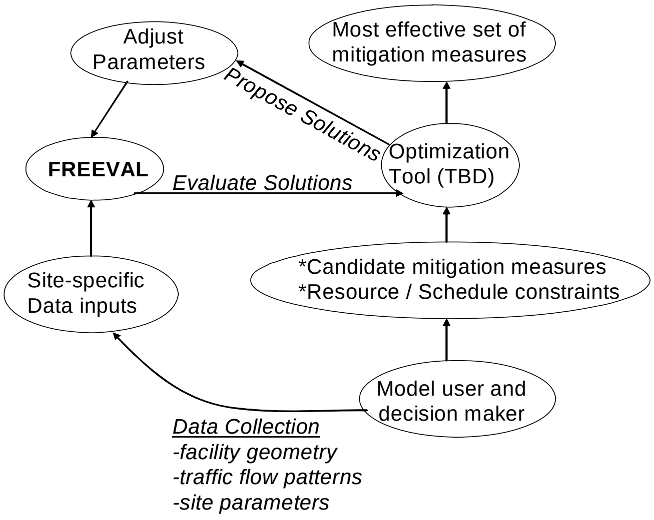
As an HCM-based product, FREEVAL estimates free flow speed (FFS) and capacity values based on the freeway procedures for basic, weaving and ramp segments as presented in Chapters 23 → 25 of the HCM2000. These default parameters can be altered in FREEVAL using field-measured FFS (a capability that currently exist), and capacity adjustment factors that can be made to vary by segment and time interval. The latter adjustments, however, are carried out with the assumption that the base HCM capacities are correct, and therefore may not necessarily reflective of locally measured capacities. The same limitations apply to those two parameters for on-ramp and off-ramp roadways. In addition, because FREEVAL has the capability to model temporary capacity reductions due to incidents or work zones, it would be important to enable the model to accept direct data entry of incident and work zone capacities and speeds as inputs. In this case, the HCM FFS and capacity computations (and assumptions) can be totally by-passed. The model then proceeds directly to computing performance measures at the segment, time interval and facility levels.

B-1 Implementing Field-Verified Mainline Capacities in FREEVAL: This enhancement can be implemented in the FREEVAL main menu, similar to the current option of selecting field measured FFS. However, this will require entering individual segment capacity values for at least the first time period, and possibly more (if an incident or work zone is simulated in some intermediate time period). It should be noted that any field capacity should be reported in units of vehicles/hr, not passenger cars/hr to avoid the use of the HCM2000 heavy vehicle adjustment factor. With the calibrated FFS and capacity value, FREEVAL will generate the appropriate speed-flow curve for each segment.

B-2 Implementing Field-Verified Ramp Capacities in FREEVAL: This enhancement is identical to B-1 but applies to ramp roadway segments, both on and off ramps. This enhancement also works in concert with those described under projects A-1 and A-2 above.

3.3 Incorporating a Bottleneck Mitigation Decision Support Tool in FREEVAL (Class-C)

At its core, bottleneck mitigation measures on a freeways facility can be viewed as a limited resource allocation problem in both the time and space dimensions. These classes of problems consider budgetary, scheduling and manpower constraints on the type, magnitude and duration of implementation of the various bottleneck congestion mitigation measures. The decision support tool to be integrated within FREEVAL is aimed at enabling users to quickly enter site-specific information, list a set of *candidate* mitigation measures or solutions, specify the practical limitations in terms of resources that can be expended and any other constraints on the scheduling or sequencing of activities. The tool will interface with FREEVAL, and will propose an *optimal* set of bottleneck mitigation measures, their sequence and budget implications. The objective function used in evaluating candidate solutions is to *minimize the total facility delay, including that incurred by traffic on the on-ramps.* Delay is defined as the difference in actual travel time and travel time at the facility free flow speed. The integration process is illustrated in the simplified schematic below. Classical, non-linear optimization/search tools including genetic algorithm, simulated annealing and gradient search techniques will be considered for this class of problems [7].



C-1 Mitigation Measures within the existing ROW

Bottleneck mitigation measures that do not require additional construction or re-striping are considered in this category. This would include the use of right or left shoulders as travel lanes during peak periods. The decision variables in this case are the shoulder segment designation, shoulder activation time interval, shoulder deactivation time interval, and activation side (right vs. left). Constraints include segments where the use of shoulders lanes may not be feasible (e.g. narrow bridges) and maximum number of shoulder lane miles that can be implemented on the facility. Two operational parameters, namely free flow speed and segment capacity, will be adjusted on those segments where shoulder lanes will be activated, and only during the activation periods.

C-2 Mitigation Measures that require re-configuring the existing ROW

This class of measures includes new construction or re-striping. The decision variables in this case are segments that will be widened, and segments that will be re-striped to add (narrower) lanes within the existing cross-section. An important distinction between C-2 and C-1 measures is that C-2 measures are considered to be permanent, so that activation duration is not an issue here. Constraints include the maximum number of lanes that can be accommodated in each segment (basically a minimum lane width constraint), and the number of new lane miles of construction that can be added (a budget constraint). The same two operational parameters of free flow speed and segment capacity will need to be adjusted accordingly when B-2 measures are implemented on the facility.

C-3 Ramp Control Mitigation Measures

While C-1 and C-2 were capacity-oriented measures, C-3 mitigation measure are intended to control the flow or demand on the facility. Two specific strategies are included: ramp metering, and flow diversion. With ramp metering, the decision variables are which on-ramps and in which time interval(s) a specific ramp metering rate should be applied, subject of course to pre-specified minimum and maximum metering rates, and a maximum number of ramp-meters. In the flow diversion case, the objective is to select the location of and minimum diversion percentage at exit ramps. One could think of this treatment akin to the presence of a changeable message sign that will induce diversion away from the bottleneck location. Of course, there would be an upper bound on the number of diversion points, and diversion percentage. The issue of how to handle the effect of diverted traffic is unclear at this point since FREEVAL calculates impacts on the freeway facility only, so the effect of the diverted traffic on other roads in the network cannot be accounted for at this time without a major extension to FREEVAL to model (at least) one alternative surface street facility. Alternatively, a separate analysis for the diverted traffic could be carried out using other macroscopic traffic modeling tools such as the HCM arterial Chapter or a simplified planning level model such as ARTPLAN [8].

3.4 Streamlining FREEVAL output for Bottleneck Analysis Applications (Class-D)

The project interim report [9] has provided detailed definitions of recurring freeway bottlenecks, and associated potential mitigation measures for each. Three bottleneck types have been identified:

- Type I bottleneck which occurs as a result of a demand surge, with no capacity reduction (most common: on-ramp merges)
- Type II bottleneck which occurs as a result of capacity reductions, with no demand surge (most common: lane drops, steep grades, , narrow lanes, tunnels) and
- Type III bottleneck which occurs as a result of combined demand surge and capacity reduction (weaving sections)

In addition, the report suggests that Type I, and to some extent Type III bottlenecks, which may require some demand management scheme (ramp metering or diversion) to mitigate the negative impacts of those bottlenecks should be analyzed at the corridor or network level. This recommendation ensures that the observed problems on the freeway facility due to demand surges are not simply migrated elsewhere in the network. The report also recognizes that macro models such as FREEVAL are important in the process of identifying the bottleneck location, severity and duration. It can also be used as a first cut tool to investigate the likelihood that demand management strategies will have a significant spill over effect beyond the facility.

The new bottleneck reports proposed in FREEVAL will be, as much as possible consistent in content with those derived from on-line data, as presented in Chapter 4 of the interim report. They will be supplemented with additional information that is not currently reported from on-line data, but is available from FREEVAL outputs. For the sake of consistency, all enhancements are combined into two projects related to bottleneck impacts and effects of mitigation measures.

<ins>D-1 Generating Bottleneck-Specific Impacts:</ins>

In this proposed enhancement, the FREEVAL code will be extended to generate bottleneck-specific reports, which will include at a minimum the following attributes for each bottleneck:

- *Bottleneck location and severity*: A bottleneck is always defined as a freeway segment which experiences a d/c ratio that exceeds 1.0 for at least one time interval (which could vary in length depending on the facility). This definition is different from the on-line model cited in the interim report, which specifies four speed-based conditions (from detectors) to identify the location of an active bottleneck. The severity rating is directly proportional to d/c.
- *Bottleneck Type*: Based on the input data stream into the model, a bottleneck will be categorized as Type I, II or III. In addition, each

bottleneck will be labeled as active (if it results in upstream queuing) or hidden if it does not. Thus a Type I-A bottleneck is an active bottleneck of Type I, while a Type III-H would be a hidden bottleneck of Type III. Note that depending on the traffic demand profile, a hidden bottleneck in one time period could be activated in a subsequent time period. In this case, two (or possibly more) reports would be generated for the same bottleneck during its active and hidden phases.

- *Bottleneck Spatial Extent*: This performance measure represent the furthest upstream extent of the queue (in miles) associated with an active bottleneck. A queue in FREEVAL is defined as any traffic flow regime whose density exceeds the density at capacity. This is slightly different from the definition in the algorithm that relies on on-line data, where a queue is defined via a maximum speed threshold of 40 mph.
- *Bottleneck Temporal Extent*: This measure represent two time stamps announcing the activation and de-activation of the recurring bottleneck. The start time in FREEVAL will always be at the start of one time interval (where for example the demand surge occurs). The end time represents the minute within a time interval in which the upstream queue has cleared. For example, if the model was running in 15 minute time intervals, and an active bottleneck was detected in interval 3, and the queues dissipated in minute 10 of interval 5, the start time would be 45 minutes, the end time would be 85 and the duration would be 40 minutes.
- *Bottleneck Delays:* FREEVAL calculates vehicle-hours of delays on each segment for each time interval. This measure aggregates the delays on those segments and time intervals in which a queue was present. As stated earlier, delay is defined as the difference in actual and free flow travel time for the effected segments multiplied by the segments’ flow counts. Its computation is very similar to the algorithm that relies on real time data except that the latter uses a pre-specified average free flow speed of 60 mph.

D-2 Generating Bottleneck Mitigation Measures Report

The output report in D-1 describes the “baseline” conditions on a freeway facility before any bottleneck mitigation measures are implemented. In practice, the user could simply code a new input file which includes some bottleneck mitigation measures (e.g. add an auxiliary lane at the bottleneck section), generate a second output similar to D-1 and compare the performance between the two runs. Also, if the decision support tool described in section 3.3 is implemented as part of the FREEVAL enhancement, it would automatically generate the optimal mitigation measures and report their relative effectiveness (e.g. delays) compared to the baseline condition. In this case, enhancement D-2 would also not be needed. Therefore D-2 starts with the premise that the user will input a set of mitigation measures manually into FREEVAL, and would be looking for the model to produce comparative statistics from the baseline and "improved" conditions. D-2 will therefore implement a capability to make "batch runs" in FREEVAL, compare the results across pairs (or more) of runs, and report on the relative effectiveness of different mitigation measures.

3.5 Minor Enhancements and Corrections to Output (Class-E)

These enhancements are aimed at improving the formatting, ease of understanding and readability of FREEVAL outputs. These are listed in bullet form below.

- E-1: Add segment and/or ramp name or other designation in all output reports
- E-2: Ensure consistency in reporting the correct units throughout the output (metric vs. US)
- E-3: Ensure that all graphs have consistent type, scale and visual effect
- E-4: Incorporate actual segment length in all 2-D and 3-D charts, as opposed to segment numbers.
- E-5: Improve the labeling of the various interval and overall output tabs.
- E-6: Ensure consistency in output results when the duration of the time interval in which demand and/or capacity is allowed to vary (Note: most of the production runs in FREEVAL were conducted assuming a 15 min interval size).
- E-7: Ensure that field calibrated inputs are not duplicated in other input screens in FREEVAL.

Table 1 Summary of Proposed FREEVAL Enhancements

CLASS	**Project Title**	**Evaluation Criteria**				
		Priority (ITRE)	Costs (relative)	Time to Complete (Months)	Short Term Benefit	Long Term Benefit
A-Algorithm Improvements	1-Off-ramp model enhancement	H	M	**12**	H	M
	2-On-ramp model enhancement	M	M		M	L
	3-Queue allocation to mainline and ramp	H	M		H	H
	4-Capacity during queue discharge	M	L		M	H
	5-Automated estimation of demand	L	H		L	M
B- Field	1-Field calibrated mainline capacity inputs	H	L	**6**	H	H
	2-Field calibrated ramp capacity inputs	H	L		H	H
C- Decision	1-Mitigation measures within ROW	M	H	**12**	M	H
	2-Mitigation measures, re-config. ROW	M	H		M	H
	3- Ramp control mitigation measures	M	H		M	H
D- Bottle.	1- Bottleneck impact report	H	M	**3**	H	H
	2- Bottleneck mitigation impact report	H	H		M	H
E- Format Enhancements	1-Add segment names to output	M	L	**3**	H	M
	2-Ensure consistency in units in output	M	L		H	M
	3- Ensure consistency in graphs	M	L		H	M
	4- Use actual segment lengths in graphs	M	M		H	M
	5- Improve labeling of time intervals	L	L		M	M
	6- Check for consistency when int. ≠ 15 min	H	M		H	H
	7- Avoid input duplication when using calibrated field data	M	M		M	H

Cited References

1. *Low-Cost Improvements for Recurring Freeway Bottlenecks.* Transportation Research Board, NCHRP 3-83. Research Proposal Plan, April 2005.

2. *Highway Capacity Manual 2000.* Transportation Research Board, Washington, DC, 2000.

3. Hall, F. L., L. Bloomberg, N. M. Rouphail, B. Eads, and A. D. May. Validation Results for Four Models of Oversaturation Freeway Facilities. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1710,* TRB, National Research Council, Washington, DC, 2000, pp 161-170.

4. Eads, B. S., N. M. Rouphail, A. D. May, and F. L. Hall. Freeway Facility Methodology in *Highway Capacity Manual 2000.* In *Transportation Research Record: Journal of the Transportation Research Board, No. 1710,* TRB, National Research Council, Washington, DC, 2000, pp 171-180.

5. May, A. D., N. M. Rouphail, L. Bloomberg, F. L. Hall, and T. Urbanik. Freeway Systems Research Beyond *Highway Capacity Manual 2000.* In *Transportation Research Record: Journal of the Transportation Research Board, No. 1776,* TRB, National Research Council, Washington, DC, 2001, pp 1-9.

6. Persaud, B.N., and V.F. Hurdle, Freeway Capacity: Definition and Measurement Issues, in *Proceedings, International Symposium on Highway capacity, Ed:* Ulrich Brannolte; Karlsruhe, July 24-27, 1991, pp. 289-307.

7. Hillier, F.S., and Lieberman, G.J., Introduction to Operations Research 5th Edition, Mc. Graw Hill Book Company, 1990.

8. Washburn, S. S., K. G. Courage, and T. Nguyen. Integrated Simulation-Based Method for Estimating Arrival Type for Signalized Arterial Planning Applications. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1852,* TRB, National Research Council, Washington, DC, 2003, pp 69-76.

9. *Low-Cost Improvements for Recurring Freeway Bottlenecks*. Transportation Research Board, NCHRP 3-83. Interim Report, December 2006.