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Development of an Optimal Ramp Metering Control Strategy for I-12

by

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16. Abstract
This study presents a comprehensive evaluation of various adaptive ramp metering strategies in order to identify the optimum algorithm that can help improve traffic conditions on I-12, Baton Rouge, Louisiana. The evaluated ramp metering strategies included the ALINEA local ramp metering control and mixed strategies case which included HERO coordinated and the local ALINEA control. The coordination was performed between three sets of two on-ramps, one on the eastbound and two on the westbound, while the other on-ramps were operating as ALINEA. The different strategies were compared to the current ramp metering strategy that was fixed-time. Geometric and traffic data were collected to build and calibrate a simulation model to be used to test the different ramp metering strategies. Comparative evaluation was then performed on the simulation results of the three strategies using three performance measures: travel time, speed, and vehicle hours travelled (VHT). The three measures were aggregated for the entire corridor and averaged for different sections on the corridor while each section was representing a ramp metering location. The evaluation was conducted separately for the eastbound and westbound directions. For the eastbound direction, the average travel time reduction was 2 seconds for ALINEA and 6 seconds for the mixed strategy case. For the travel speed, the average increase in speed was 0.2 mph for the ALINEA control and 0.4 mph for the mixed strategy. For the VHT, the average reduction was 2.5 veh.hrs for the ALINEA control and 6.5 veh.hrs for the mixed strategy case. On the other hand, for the westbound direction, the results showed more significant improvements. The average travel time reduction increased to 20 seconds for ALINEA control and 40 seconds for the mixed strategy case. For the travel speed, the average increase in speed was one mph for the ALINEA control and 2 mph for the mixed strategy. For the VHT, the average reduction was 195 veh.hrs for the ALINEA control and went up to 197 veh.hrs for the mixed strategy case. The statistical analysis on these results showed that while the improvements were not significant for the eastbound, they were significant for the westbound direction. Yet, most of the results were not considered practically significant. Therefore, more detailed section-by-section analysis was performed using the calculated performance measures for each section on the corridor. The section-by-section analysis showed that none of the eastbound sections experienced any significant improvements. Whereas, on the westbound direction, three sections experienced significant improvements in the different performance measures: Range-O'Neal, O'Neal-Millerville, and Millerville Sherwood. The travel time reductions on these sections were as high as 45 seconds and 30 seconds for ALINEA and the mixed strategies, respectively. The increase in speed was 9 mph and 13 mph for ALINEA and the mixed strategies, respectively. For the VHT, both strategies achieved reductions that reached 100 veh.hrs for the three sections. When the ALINEA and mixed strategies where compared to one another, the mixed strategy showed more significant improvements. In summary, the eastbound did not experience any significant improvements in the traffic conditions. This is expected since this direction is operating at free flow conditions with the fixed-time strategy. On the other hand, for the westbound directions, the mixed strategy improved the traffic conditions significantly compared to the other control strategies. Yet, the achieved improvements were not as significant as expected. This was caused by the spillbacks at the off-ramps resulting from the vehicles waiting at the red traffic signals on the surface streets. Therefore, the study recommended investigating the integrated corridor management between the ramp meters and the traffic signals on the surface streets.

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This study presents a comprehensive evaluation of various adaptive ramp metering strategies in order to identify the optimum algorithm that can help improve traffic conditions on I-12, Baton Rouge, Louisiana. The evaluated ramp metering strategies included the ALINEA local ramp metering control and mixed strategies case, which included Heuristic Ramp Metering Coordination (HERO) coordinated and the local ALINEA control. The coordination was performed between three sets of two on-ramps, one on the eastbound and two on the westbound, while the other on-ramps were operating as ALINEA. The different strategies were compared to the current ramp metering strategy that was fixed-time.

Geometric and traffic data were collected to build and calibrate a simulation model to be used to test the different ramp metering strategies. Comparative evaluation was then performed on the simulation results of the three strategies using three performance measures: travel time, speed, and vehicle hours travelled (VHT). The three measures were aggregated for the entire corridor and averaged for different sections on the corridor while each section was representing a ramp metering location. The evaluation was conducted separately for the eastbound and westbound directions.

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The section-by-section analysis showed that none of the eastbound sections experienced any significant improvements. Whereas, on the westbound direction, three sections experienced

significant improvements in the different performance measures: Range-O'Neal, O'Neal-Millerville, and Millerville-Sherwood. The travel time reductions on these sections were as high as 45 seconds and 30 seconds for ALINEA and the mixed strategies, respectively. The increase in speed was 9 mph and 13 mph for ALINEA and the mixed strategies, respectively. For the VHT, both strategies achieved reductions that reached 100 veh.hrs for the three sections. When the ALINEA and mixed strategies where compared to one another, the mixed strategy showed more significant improvements.

In summary, the eastbound direction did not experience any significant improvements in the traffic conditions. This is expected since this direction is operating at free flow conditions with the fixed-time strategy. On the other hand, for the westbound directions, the mixed strategy improved the traffic conditions significantly compared to the other control strategies. Yet, the achieved improvements were not as significant as expected. This was caused by the spillbacks at the off-ramps resulting from the vehicles waiting at the red traffic signals on the surface streets. Therefore, the study recommended investigating the integrated corridor management between the ramp meters and the traffic signals on the surface streets.

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IMPLEMENTATION STATEMENT

Ramp metering with fixed time control was implemented in June 2010 on I-12 in Baton Rouge between Essen Lane and Walker South Road/LA 447 from June to November 2010. The main objective was to reduce the frequency of breakdowns and improve the operational efficiency of traffic. The ramp metering is operated with a fixed cycle length (2 seconds of green/2 seconds of red) during the morning peak hours (6:00 to 9:00 a.m.) for the westbound traffic and during the evening peak hours (3:00 – 7:00 p.m.) for the eastbound traffic. A recent evaluation of the effectiveness of the ramp metering strategy concluded that the fixed time operation of the control system did not yield significant reductions in congestion along the corridor. This report presents findings of the evaluation of the effectiveness of a local responsive ramp metering strategy and a coordinated ramp metering strategy. The findings of this report provide an objective assessment of the benefits of the adaptive ramp metering strategies on I-12 to the officials of DOTD and other interested transportation officials within Louisiana. Based on the reported findings of this study, recommendations were made to consider using the adaptive strategies. In addition, the study recommends investigating the integrated corridor management between the ramp meters and the traffic signals on the surface streets at the end of the off-ramps.

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INTRODUCTION

Urban freeways in major cities in the U.S. are operating near- or beyond-capacity conditions during peak periods due to increased travel demand. Such conditions often result in traffic breakdowns and heavy congestion, which continue to escalate and spread over the surface transportation network in the U.S. The transportation community of practitioners, researchers, and public agencies now recognizes the need for better management of the existing network capacity as a viable alternative to capacity expansion projects. In recent years, more emphasis has been placed on Active Traffic Management (ATM) strategies such as ramp metering, speed harmonization, managed lanes, and others. Ramp metering is one of the successful active traffic control strategies to control the flow of traffic entering the freeway facility from on-ramps and reduce the occurrence of breakdowns at merging areas by preserving the maximum traffic flow on the mainline. Optimal ramp metering control helps reduce the breakdown probability at merging locations, which is typically caused by a sudden influx of traffic from the on-ramp attempting a forced merge with mainline traffic.

From June to November 2010, DOTD deployed ramp metering control, using a simple pre-timed operation with a fixed cycle length (2 seconds of green/2 seconds of red), along a 15-mile section of the I-12 interstate in Baton Rouge, Louisiana. Ramp metering was implemented to reduce congestion, provide a safer merge operation at freeway entrances and improve travel time reliability of the corridor. A recent evaluation study for DOTD showed slight improvements in traffic conditions at some locations with fixed time ramp meters. Other locations exhibited no improvements or deterioration in traffic conditions, which may be attributed to the construction work on I-12 at some locations at the time of analysis and/or the inability of the fixed time ramp metering strategy to cope with the varying demand on the mainline. Therefore, the study recommended further investigation to examine the feasibility of applying dynamic ramp metering algorithms on I-12, wherever applicable. Demand responsive and coordinated ramp metering strategies involve a system where the signals change every few seconds in response to freeway conditions locally or at adjacent interchanges. The signals may work as individuals or coordinated clusters to resolve complex traffic problems and reduce congestion along the freeway. In either case, the dynamic control of the signals is feasible through Freeway Control Regulators (algorithms) that tend to optimize the capacity of the freeway.

The objective of this study was to conduct a comprehensive evaluation of various ramp metering strategies in order to identify the optimum algorithm that can help improve traffic conditions on I-12. The analysis included the performance of the current fixed time ramp meters after the construction work was completed on I-12, in addition to the other ramp metering control strategies. The evaluation of performance for each ramp metering strategy was conducted using a microscopic simulation platform.

Ramp Metering Algorithms

Active Traffic Management (ATM) strategies such as ramp metering aim to improve the operation and safety of traffic by regulating the demand from on-ramps to the freeway mainstream. Also, such strategies are cost-effective, utilize existing infrastructure, and require minimal expansion to alleviate congestion in the region *[1]*. In 1960, ramp meters were implemented for the first time in Chicago, Detroit, and Los Angeles areas *[2]*. Since that first implementation, transportation researchers started to investigate different operational strategies in order to optimize the performance of ramp meters. For fixed-time metering strategies, ramp-meter timings are adjusted automatically by specified time-of-day parameters. This algorithm does not afford flexibility for changing traffic conditions. Traffic-responsive ramp metering strategies, as opposed to fixed-time strategies, are based on real-time measurements from sensors installed in the freeway network and can be classified as local or coordinated. Local control is a process of selecting ramp meter rates based solely on conditions present at an individual ramp, while coordinated control is a process of coordinating the metering rates for group of ramps based on conditions throughout the entire length of the metered corridor.

In general, for a ramp controlling methodology to be ideal, it should be accurate in describing both the operations and control in the freeway system while possessing theoretical foundation. The method must also be proactive, balanced, accurate, robust, computationally efficient, flexible, simple, expandable, and able to handle special situations *[3]*.

Local Ramp Metering Strategies

Local ramp metering strategies are those incorporating the traffic parameters only within the vicinity of the on-ramp to calculate the optimal on ramp flow rate. This section reviews the common local ramp metering algorithms developed.

Masher developed a Demand-Capacity (DC) ramp-metering algorithm, which is a traffic responsive algorithm that measures the downstream occupancy *[4]*. If it is above the critical occupancy, congestion is assumed to exist. The metering rate is then set to the minimum rate. Otherwise, the volume is measured upstream of the merge, and the metering rate is set to the difference between the downstream capacity and the upstream volume.

The occupancy (OCC) strategy is an occupancy-based feed forward strategy, which is even more inaccurate than the DC strategy due to the linearity assumption for the fundamental diagram and the uncertainty *[5]*. This strategy uses only upstream sensor occupancy measurements to identify and measure congestion. The critical occupancy is measured using historical data.

Both the DC and OCC are considered open-loop systems. In such systems, the output from the system is not used as input for the next iteration. These systems are unreliable due to the lack of feedback mechanism, unlike the ALINEA algorithm proposed by Papageorgiou *[6]* *[7]*. The ALINEA is a local responsive feedback ramp metering strategy, which has had multiple successful field applications (Paris, Amsterdam, Glasgow, and Munich). This algorithm considers traffic flow as the process being controlled and the metering rate as the control variable. Based on the feedback control theory, the algorithm attempts to set the metering rate such that traffic flow will not exceed system capacity. The algorithm uses the difference in occupancy values (desired or capacity versus measured), measured at a point 12 ft. downstream of the ramp gore, to calculate a metering rate. One of the most desirable features of this closed loop algorithm is the integration of the previous time interval metering rate within the equation. This allows integrated smoothing of the metering rates to avoid wide swings between concurrent time intervals. The ALINEA algorithm is easy to implement because of the minimal requirements. However, it does not consider queue spill-back directly, which is generally handled through overriding restrictive metering rates, and would have difficulty to balance freeway congestion and ramp queues when traffic becomes heavily congested *[3]*.

In another paper, Smaragdis presented several modifications and extensions of ALINEA. Specifically, FL-ALINEA is a flow-based strategy; UP-ALINEA is an upstream occupancy-based version; UF-ALINEA is an upstream-flow-based strategy *[6]*. X-ALINEA/Q is the combination of any of the above strategies with efficient ramp-queue control to avoid interference with surface street traffic.

A zone algorithm was reported as used in Minnesota *[8]*. This algorithm defines directional freeway facility "metering zones" with zones having variable lengths of three to six miles. The basic concept of the algorithm is to balance the volume of traffic entering and leaving each zone. All entering and exiting traffic volumes on both the mainline and the ramps are measured in 30-second increments, and balancing these total volumes is used to keep the density of traffic within the zone constant.

Ghods proposed an adaptive genetic fuzzy control approach to reduce peak hour congestion, along with speed limit control *[9]*. To calibrate the fuzzy controller, a genetic algorithm is used to tune the fuzzy sets parameters so that the total time spent in the network remains minimum. The proposed method is tested in a stretch of a freeway network using a macroscopic traffic model in an adaptive scheme.

Ozbay developed an isolated feedback-based ramp-metering strategy that takes into account the ramp queue *[10]*. In addition to the regulation of ramp input, the strategy calls for regulation of ramp queues by explicitly incorporating them into the model. This isolated ramp-metering strategy is tested using PARAMICS, a microscopic traffic simulation package, on a calibrated test network located in Hayward, California. The strategy was found to be effective in optimizing freeway traffic conditions (reduction in mean congestion duration on the freeway downstream link, mean downstream occupancy, and travel time).

Coordinated Ramp Metering Strategies

Unlike local ramp metering strategies, coordinated strategies account for the traffic conditions at a set of consecutive ramps. Coordinated ramp metering strategies have been suggested as more effective than local ramp metering especially when there are multiple congestion bottlenecks on the freeway, excessive ramp delays, and when the performance optimization of freeway and on-ramps requires the metering of several ramps. Many coordinated strategies were developed using different controlling parameters. In this section, different strategies are reviewed.

The bottleneck metering algorithm is a system ramp control, which includes several internal adjustments of a volume reduction based on downstream bottlenecks and localized adjustments, such as queue override *[11]*. At the local level, historical data is used to determine approximate volume-occupancy relationships near capacity for each ramp location. Local metering rates are then calculated to allow ramp volumes to equal the difference between the estimated capacity and the real-time upstream volume. The coordinated bottleneck algorithm is activated when the following two criteria are met: (1) downstream bottleneck-prone section surpasses a pre-determined occupancy threshold, and (2) the “zone” or area of influence upstream of the bottleneck is storing vehicles. The algorithm then uses centrally assigned metering rate reductions applied to meters in the zone to reduce the number of vehicles entering the mainline by the number of vehicles stored in the bottleneck area of influence.

ARMS (Advanced Real-time Metering System) consists of three operational control levels within a single algorithm: free-flow control, congestion prediction, and congestion resolution *[12]*. Flow is treated as a semi-static process in which traffic flow varies slowly with time, where the control decisions are based on a free flow model. Congestion prediction works to predict (and thus pre-empt) traffic flow breakdowns caused by dynamic traffic fluctuations. Traffic flow is modeled as a rapidly changing dynamic process. Combining this control module with the free-flow control module provides for an environment in which the probability of congestion occurring is reduced. Congestion reduction is a dynamic algorithm that balances congestion resolution time and metering rates by integrating both freeway and surface street operations. This algorithm has been successfully tested in simulation models.

Wei developed a coordinated metering algorithm using artificial neural networks. This algorithm is based on an Artificial Neural Network (ANN) with a “learning” capability *[13]*. It is used in an offline capacity to generate an initial, preliminary metering plan, which is used within a back-propagation algorithm to “train” the neural network. The roadway system is divided into control zones, and input data for the algorithm is collected at each ramp in a zone, V/C ratios upstream and downstream of the ramp and the ramp queue length on each ramp. As the metering rate for each on-ramp is affected primarily by the mainline V/C measurements near the ramp and only partially by the traffic conditions elsewhere in the zone, a partially connected neural network is used.

The internal model tracks the actual traffic conditions, the implemented control strategies, and the results. This information is evaluated and, if necessary, additional self-adjustment training data is provided for the ANN system until the desired traffic condition is reached.

Seeking to address the interaction of the freeway system with the adjacent surface-street system, Gettman presents a multi-objective integrated large-scale optimized ramp metering system for freeway traffic management *[14]*. This was done by providing a method to trade-off queue growth at individual ramps in a freeway corridor. The system is composed of three primary components: area-wide metering rate coordination, predictive-cooperative real-time rate regulation, and anomaly detection/optimization scheduling. The area-wide rate coordination algorithm is based on a multi-criteria quadratic programming problem. The predictive-cooperative real-time rate regulation algorithm is a pro-active approach to local traffic-responsive control using “scenario based” linear programming. Re-optimization intervals of the area-wide coordination and the predictive-cooperative real-time rate regulation algorithms are scheduled by a process monitoring function based on concepts in statistical process control. The performance of the method was evaluated using a simulation test case for a typical three-hour peak period on a realistic freeway in Phoenix, AZ, in freeway average speed, total travel time, queue time, and congestion recovery time.

Zhang developed a new freeway ramp control objective: minimizing total weighted (perceived) travel time, which is presented in this study *[15]*. This new objective function is capable of balancing efficiency and equity of ramp meters, while the previous metering objective, minimizing total absolute travel time, is purely efficiency-oriented and hence produces a most efficient but least equitable solution. Consequently, a ramp control strategy BEEX (Balanced Efficiency and Equity) was developed. BEEX seeks to minimize the total weighted travel time, which involves weighting both the freeway mainline travel time and the ramp delays.

A ramp metering algorithm incorporating “fuzzy logic” decision support was developed at the University of Washington *[16]*. This algorithm was installed in early 1999 by WSDOT, controlling 15 metered ramps along I-405. The algorithm, based on fuzzy set theory, is designed to overcome some of the limitations of existing conventional ramp metering systems. In a simulation-based evaluation using FREeway SIMulation (FRESIM) and a model of the Seattle I-5 corridor, the fuzzy controller demonstrated improved robustness, prevented heavy congestion, intelligently balanced conflicting needs, and tuned easily. The objective was to maximize total distance traveled, minimize total travel time and vehicle delay, and still maintain acceptable ramp queues. This algorithm functions on two levels and provides both local and downstream bottleneck metering rate selection.

A freeway traffic control system has been in place on the Hanshin Expressway near Kobe, Japan. The Hanshin algorithm is based on Linear Programming formulation *[17]*. The linear algorithm maximizes the weighted sum of ramp flows. It also computes a real-time capacity for each road segment. The algorithm requires a very comprehensive data collection system with detectors closely spaced on the mainline and multi-point detection on all exit/entrance ramps. To solve for metering rates, the algorithm uses both real-time and pre-defined system variables as well a number of tuned parameters and weighting factors for a series of ramps. The performance of the algorithm is heavily dependent on accurate origin-destination data.

Another coordinated ramp metering strategy, METALINE, is a coordinated generalization (using lists of multiple values, or columnar vectors, in place of single values) of ALINEA *[18]*. The metering rate of each ramp is computed based on the change in measured occupancy of each freeway segment and the deviation of occupancy from critical occupancy for each segment that has a controlled on-ramp. This algorithm incorporates a smoothing feature from the ALINEA algorithm, preventing wide swings in metering rates between concurrent time intervals by incorporating the previous metering rate into the equation for calculating the next time interval metering rate. The sensitivity of this algorithm is also quite high, as it responds to the change in occupancy between time intervals, rather than the overall occupancy of the system, allowing more responsive operation for smaller changes in traffic flow.

Chang proposed a metering model for non-recurrent congestion. This algorithm uses a two-segment linear flow density model *[19]*. Kalman filtering and auto-regressive moving average techniques are used for estimating link densities and ramp queue lengths from point volume and occupancy detector data and traffic system model parameters. A dynamic equation for density evolution, according to the flow conservation law, is formulated to describe the freeway traffic system and ramp traffic dynamics. The traffic evolution equations act as the essential constraints for optimizing metering rates. Other constraints are the lower and upper physical bounds on the mean link densities, the maximum and minimum allowable metering rates, and the maximum allowable ramp queue length. Traffic flow or throughput is then solved for within the objective function using linear programming mathematics.

As the successor of the ZONE metering algorithm, the Stratified Zone Ramp Metering (SZM) Strategy has been developed and deployed in the Minneapolis/Saint Paul area *[20]*. The SZM strategy aims in maximizing freeway throughput while keeping ramp waiting times below a predetermined threshold. It focused on a better determination of the minimum release rate for each ramp and its integration with the overall SZM strategy. The SZM strategy is tested in two freeway sites under various demand scenarios through a state-of-the art microscopic simulator. The simulation results indicate that the SZM strategy is effective in delaying and decreasing the freeway congestion as well as resulting in smoother freeway traffic flow.

In a recent study, Papamichail developed a traffic-response feedback control strategy, HERO (Heuristic Ramp Metering Coordination), to coordinate local ramp metering actions in freeway networks *[21]*. In the framework of HERO, ALINEA ramp metering strategy was applied to each on-ramp, the desired ramp flow was calculated, and the ramp queue was estimated. The coordination using HERO was materialized via occasional appropriate setting of minimum ramp-queue lengths that should be created and maintained at specific ramps. A pilot project of HERO has been implemented in Melbourne, Australia, as a part of the Monsh-Citylin-West Gate (MCW) upgrade. Another HERO strategy implementation took place on the M1/M3 freeway in Queensland, Australia. Faulkner *[22]* investigated the impact of HERO on the performance of the freeway and found that the traffic throughput and travel times improved significantly compared to the fixed-time ramp metering strategy.

Wang proposed an area-wide ramp metering system to improve the coordination of ramp meters for system-wide optimization and on-ramp overflow minimization *[23]*. It uses the principles of a computer network congestion control strategy, which reduces certain types of congestion at a targeted freeway location through limiting on-ramp vehicle flows to a fraction of ramp demand and then additively increasing rates to avoid ramp queue spillover onto city streets. The effectiveness of this ramp metering approach has been evaluated by microscopic simulation experiments.

Kwon introduced a density-based adaptive ramp metering strategy *[24]*. The new strategy is based on a “segment density” and adopts an implicit coordination approach in determining the rates of each meter to manage the flows at bottlenecks. The new algorithm is coded with the Java language and incorporated into the current version of Intelligent Road Information System (IRIS). IRIS is a computerized operating system developed by the Minnesota Department of Transportation (MnDOT) to operate field devices such as ramp meters. Then, this metering algorithm is evaluated with the IRIS-in-Loop simulation system (ILSS), which has been equipped with the new metering module as described above. The proposed algorithm showed significant reduction of the delayed vehicle hours and lost vehicle miles traveled because of congestion, while maintaining similar or slightly higher values of the total vehicle miles traveled than the current metering method. The speed contours also show the reduced congestion level throughout the test corridor, which includes multiple bottlenecks because of the relatively short ramp-to-ramp distances.

Recently, Torne proposed a coordinated ramp metering strategy with Dynamic Speed Limits *[25]*. This strategy is based in a formulation that captures the endogenous merge capacity. They performed a cell transmission model extension. This strategy reduces the capacity drop occurrence in the vicinity of an on-ramp. Results show improvement in the performance indicators of the system such as total travel time spent (TTS), speed, flow, density, and ramp queue length.

Another project on HERO and ALINEA algorithms is by Li *[26]*. Li et al. combined previous methods with Variable Speed Limit (VSL) for a critical bottleneck section of Auckland Motorway using AIMSUN micro-simulation. Results presented that HERO combined with VSL control strategy has outperformed all other control strategies.

Ramp Metering Evaluation Studies

Similarly, several studies have been conducted to evaluate the overall benefits of ramp metering in terms of throughput, travel speeds, and travel times on the mainline. For instance, Bhouri and Kaupplia evaluated the travel time reliability benefits of ramp metering based on a study of a segment of the French motorway A6W, which comprises of five on-ramps and lasts for 20 kilometers *[27]*. The study applied four different ways to measure the travel time reliability: statistical range methods, buffer time methods, tardy trip measures, and probabilistic measures. The study concluded that different reliability measuring methods lead to inconsistency of results, and that in order to reach the optimal policy solutions, the benefits from improvement of average travel time and from improvement of travel time reliability need to be separated.

The Washington State Department of Transportation (WSDOT) reported that ramp meters reduced the risk of merging accidents on several of its major highways and freeways. Similar safety observations, attributed to ramp meters, have been made by the Georgia Department of Transportation, and the California Department of Transportation. Another practical case showing evidence of the merits of ramp metering is that of the Twin Cities in Minnesota, which had 430 active ramp meters turned off during the fall of 2000 due to the public questioning its effectiveness. The results were a decline in through traffic by 14%, a doubling of travel time unpredictability, and a 26% increase in crash rate which was the equivalent of 1,041 crashes per year.

Lee applied a real-time crash prediction model (CPM) to investigate the safety benefits of a local traffic-responsive ramp metering control (ALINEA) on the freeway *[28]*. Safety benefits were measured in terms of reduced crash potential, estimated by CPM. Traffic flow changes were captured by a microscopic traffic simulation model. The study concluded that ALINEA ramp metering control could reduce 5%-37% crash potential over the no-control case. Particularly, the crash reduction was most noticeable under the condition when congestion was caused by a high ramp traffic volume without a queue at the downstream ramp.

Wu investigated the impacts of ramp metering on driver behaviors in South England, researching the performance of drivers on ramps and on motorway carriageways with and without ramp metering *[29]*. The study concluded that ramp metering did not have significant impacts on passing traffic in terms of speeds, headway, accelerations, and decelerations. The ramp metering caused increased lane changes in pre-merge zones and thus resulted in changes of speeds and headways in pre-merge passing traffic.

In 1999, WSDOT evaluated its Renton Ramp Meters at nine locations on the I-405. Travel times and speeds were manually recorded by drivers traveling the study corridor for two weeks before and three days after the ramp meters were activated. The days chosen for evaluation were Tuesdays, Wednesdays, and Thursdays. Travel speeds, recorded at checkpoints, were averaged between checkpoints to represent segment speeds. No statistical analysis was made because of the limited number of trials. The results showed that ramp meters effectively increased speeds by 7 to 20 mph, and provided travel time savings of 3 to 16 minutes, depending on the time of day.

Zhang tested the effectiveness of ramp metering for several representative freeways in the Twin Cities during the afternoon peak period *[30]*. Seven performance measures were used to compare conditions with and without ramp metering, including mobility, equality, travel time variation, travel demand responses, etc. The study concluded that ramp metering was more helpful for long trips than short trips. Ramp metering reduced the travel time variations yet did not improve trip travel time due to ramp delays. Work-trips and non-work trips responded differently to the ramp metering control.

Zhang and Levinson studied the traffic flow characteristics at 27 active bottlenecks in the Twin Cities for seven weeks with and seven weeks without ramp metering to determine whether ramp meters increase the capacity of active freeway bottlenecks *[31]*. The authors developed a series of hypotheses concerning the relationship between ramp metering and the capacity of bottlenecks and tested the hypotheses against real traffic data. The results showed that ramp metering could increase capacity by postponing or eliminating bottleneck activation, accommodating higher flows during the pre-queue transition period than no-control, and increasing queue discharge flow rates after breakdown.

In the assessment of the Twin Cities ramp meters, the Minnesota Department of Transportation focused on three parameters: travel time, travel speed (both collected with GPS-equipped vehicles), and traffic volume (collected by loop detectors) *[30]*. Data was collected over a five-week period when ramp metering was activated, and another five-week period when ramp metering was deactivated. Statistical tests showed there were no differences between the different weekdays as well as between the different weather conditions. As such, all valid observations were grouped and analyzed together. The results showed that travel speeds on the freeway mainline improved with ramp metering by an average of 7.4 mph. The freeway throughput increased by 9% on average and 14% during peak hours. The ramp meter system provided an annual saving of 25,121 hours of travel time.

Ishak in one study applied fixed rate ramp metering strategies on the two corridors of I-10 and I-12 within the city of Baton Rouge in order to determine their effectiveness in integrated corridor management to reduce congestion on the freeway and arterial systems in Baton Rouge *[32]*. Traffic data from the city of Baton Rouge Regional Planning Council and geometric data were collected. A Friction Factor Matrix was created to determine the origin-destination flows for the morning peak period. The simulation platform used in this study is VISSIM version 5. A set of network-level performance measures was also identified as: average delay, average number of stops per vehicles, average speed, average stopped delay per vehicle, total delay time, total distance traveled, number of stops, total stopped delay, and total travel time. Comparative evaluation and statistical analysis of the identified performance measures for both metered and non-metered traffic had been done. Based on the results, the study recommends the use of ramp metering on both segments of I-10 and I-12.

Lu showed that it is necessary to coordinate all the important entrance ramps (with high demand) and relevant arterial intersections along a freeway corridor in their research project *[33]*. The objective of this project was to develop and test a practical coordination strategy between a freeway entrance ramp meter and an arterial intersection traffic signal. They developed a generic algorithm for the coordination of intersection traffic signal and freeway ramp metering. They used the ALINEA algorithm to achieve local adaptive ramp metering. The coordination strategy of the two traffic control system was formulated as adjusting some parameters in the objective function of the optimization procedure. Two approaches heuristic and system-wide optimization. A microscopic simulation model was built in Aimsun in order to evaluate the performance of the proposed control method. The limited field operational test was conducted including the development of hardware and software systems, communication interface, control algorithm, and data flows. For success of field test, a progressive system implementation and field test procedure were applied. This field test proved to be very effective to avoid any significant negative impact on traffic that could be very sensitive.

The review of the literature indicated that, for specific networks, layouts as limited ramp storage for the on-ramps and under certain traffic conditions as multiple bottlenecks on the freeway, the coordinated ramp metering strategies can provide better utilization of the freeway capacity compared to the local ones. Local ramp meters will respond to limited ramp storage for a ramp by providing excessive queue overrides on that ramp, causing increased congestion at the freeway. On the other hand, coordinated strategies will coordinate with other nearby ramps having sufficient storage available by decreasing their ramp flow rates to compensate for the ramps undergoing a shortage in storage length. However, the effectiveness of the coordinated strategies to outperform local ones depends on many variables: the number of the coordinated ramps, the relative distance between them, and the location of the bottleneck relative to them. As a result, the network in this study was simulated for both responsive strategies: the local and the coordinated ramp metering strategy. The review of the literature showed a consensus about the ALINEA being one of the most effective local strategies. That is due to the ALINEA being a feedback control scheme targeting a critical occupancy value which is believed to be constant from day to day, unlike other local strategies targeting critical capacity values that vary from day to day leading to underutilization or congestion for the freeway. As a result, the ALINEA was selected as the local ramp metering strategy for the network. However, there is no such consensus in the literature for a specific coordinated strategy, perhaps due to the limited application of these strategies in reality. Since the HERO algorithm is just a coordination of several ALINEA ramps, it was adopted for the coordinated ramp metering strategy. The fact that the HERO strategy is based on the ALINEA makes the upgrade for a number of ramps from ALINEA to HERO feasible and cost effective for the control units and the control algorithms compared to any other coordinated strategy.

OBJECTIVES

The proposed research will identify the optimal ramp metering control strategy and the anticipated operational benefits over the existing fixed-time strategy. A traffic simulation tool will be used to model the existing traffic conditions on I-12 corridor, using collected and calibrated traffic data. The most suitable algorithms to the conditions on I-12 will be tested to find the one that is capable of optimizing traffic throughput, travel time reliability, and delays on the mainline. Based on the results, the optimal strategy may be tested in the field over a short period of time before the implementation recommendation is made. Specifically, the objectives of this phase of research are to:

1. Review the state of the practice of the different ramp metering strategies and applications in other metropolitan areas in order to learn from similar experiences and identify points of strengths and weaknesses of the various strategies. This includes identification of the ramp metering strategies that were proved to be effective to improving traffic conditions in similar study areas as I-12.
2. Identify and collect the geometric and traffic data required to simulate the I-12 corridor under the selected ramp metering strategies.
3. Select a microscopic simulation platform and build the simulation network for the study corridor.
4. Calibrate the selected simulation model with the collected data to replicate the actual traffic conditions on the study corridor.
5. Identify a set of parameters and performance measures for the ramp metering strategies. Examples include travel time, delay, throughput, etc.
6. Conduct and analyze the results of multiple runs for each of the selected ramp metering strategies with different traffic demand scenarios in order to minimize the probability of breakdowns along the corridor.
7. Make final recommendations based on the main findings of the study.

SCOPE

The research is restricted to developing and testing ramp metering strategies for Interstate I-12 in Louisiana using a traffic simulation tool. Interstate highways are defined as control-of-access facilities under the federal-aid jurisdiction. The research will identify the optimal ramp metering control strategy and the anticipated operational benefits over the existing fixed time strategy.

STUDY AREA

A total of 14 ramp meters were installed in 2010 along the 15.7-mile corridor of I-12 in Baton Rouge, Louisiana, between Essen Lane and Walker South Road/LA 447. Figure 1 shows the locations of five ramp meters for the eastbound direction and nine ramp meters for the westbound direction. Since this was the first time ramp metering control was adopted in Louisiana, a simple pre-timed operation with a fixed cycle length was used. During weekdays, the meters are turned on during the a.m. peak period (6:00 a.m. – 9:00 a.m.) for westbound traffic, and during the p.m. peak period (3:00 p.m. – 7:00 p.m.) for eastbound traffic. Queue override strategy is also used for the ramps. Using video detection, as vehicles spill back on the ramps until they reach the end of the ramp at the surface streets, the ramp meters are programmed to turn green until the queued vehicles are flushed.

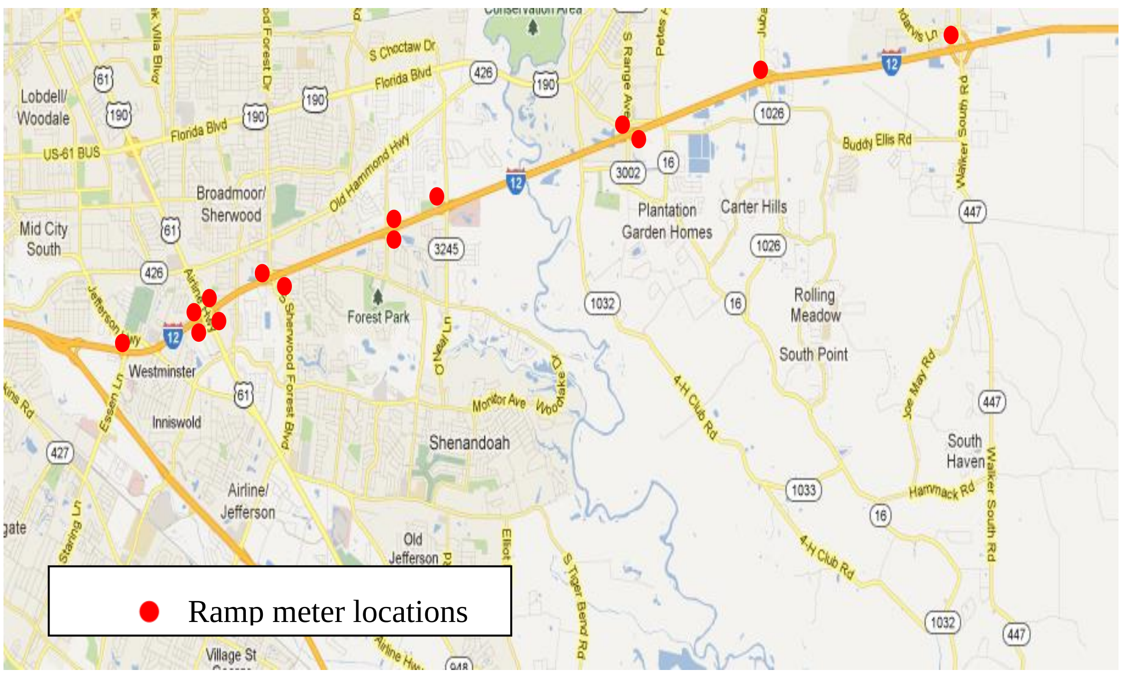


Figure 1
Study area and locations of ramp meters along the I-12 corridor

METHODOLOGY

The selected ramp metering strategies were tested using VISSIM microsimulation software that has been widely used in similar applications. Traffic simulation has been widely used because of its benefits compared to the in-situ implementation that has safety and economic concerns especially in the testing stage. The methodology of this research is depicted in Figure 2. First of all, geometric information about the study corridor was obtained from google maps. In addition, the traffic data including traffic volumes and speeds were collected from at the on-ramp and off-ramp locations over the ramp meters hours of operation. Using the geometric data, the I-12 corridor geometric network was encoded in VISSIM simulation software. Afterwards, the collected traffic data were used to calibrate the simulation model under the current fixed-time ramp metering strategy. As the I-12 simulation model is calibrated, the selected different ramp metering strategies were tested. Different performance measures were then calculated using the resulting simulation output to serve as an evaluation criteria. Using the calculated performance measures, a comparative analysis was performed between the different strategies in order to determine the optimal ramp metering strategy.

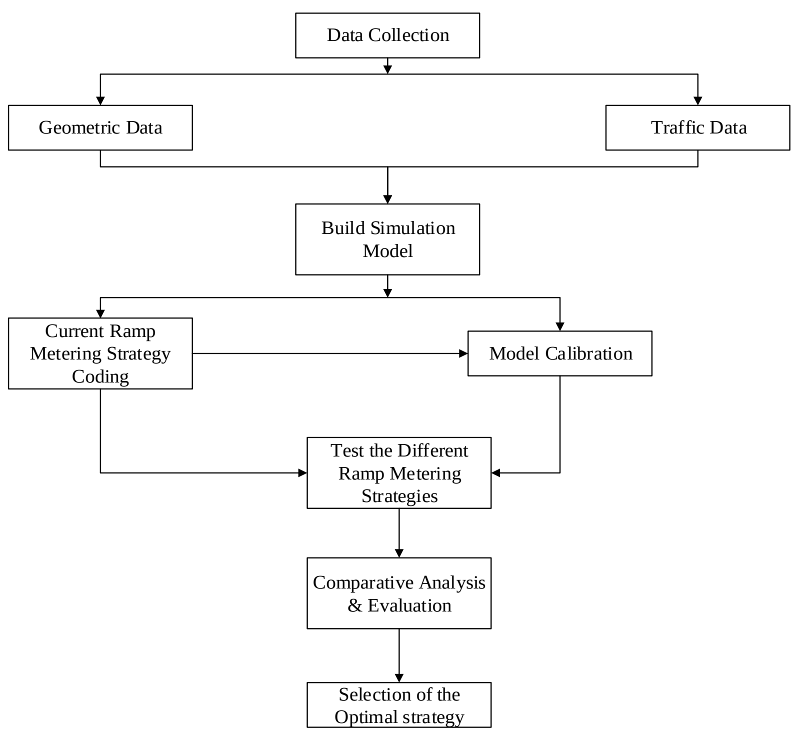


Figure 2
Research methodology

Ramp Metering Strategy

Three different ramp metering strategies were simulated for the comparative analysis: (a) fixed time strategy, which represents the current ramp metering control strategy (b) a local feedback ramp-metering strategy (ALINEA), and (c) mixed strategy, which included the heuristic traffic-responsive feedback control strategy (HERO) on some ramps and ALINEA on the rest of the ramps. The different strategies were encoded using the Vehicle Actuated Programming (VAP) interface of VISSIM and shown in Appendix A. The control methodology for the each ramp metering strategy is described in the following section.

Fixed Ramp Metering Strategy

The fixed-time strategy is the current control scheme used to operate the I-12 on-ramps. The ramp meters are set up to account for 2 seconds of green followed by 2 seconds of red time. When there are no vehicles waiting on the on-ramps to enter the mainline, the signal is set to remain red. As the vehicles start to arrive, a call is sent to the signal controllers from the presence detectors placed on the ramps so that the signal starts to turn green. During each of the fixed 2 seconds of green, a single vehicle is allowed to enter the I-12 mainline.

Queue override strategy is used in addition to the fixed-time ramp control strategy. Queue detectors are placed at the end of each ramp so that, as the ramp queues reach the detector locations, the ramp meter traffic signal turn to continuous green to flush the ramp queues.

Local Traffic Responsive Strategy: ALINEA

Local traffic responsive strategy (ALINEA) is a dynamic, local, and closed loop measure strategy that reflects the variation in the mainline and ramp volumes. ALINEA estimates the metering flow rate based on the difference between the actual downstream traffic occupancy and a desired occupancy value that is assigned by the designer. The ramp flow value $r(k_c)$ for each predefined time step k_c is determined by,

$$r(k_c) = r(k_c - 1) + K_R[\hat{O} - O(k_c - 1)] \tag{1}$$

where , $r(k_c)$ and $r(k_c - 1)$ are the ramp metering flow rates for the current and the previous time steps, K_R is a regulator parameter that is recommended to be set to 70 veh/hr, $\hat{O}$ is the desired downstream occupancy, and $O(k_c - 1)$ is the downstream occupancy measured at the previous time step. Using the ramp metering flow rate, the signal timing is updated using the following equation:

$$RedInterval(k_c) = \frac{3600}{r(k_c)} \cdot Number\ of\ Metered\ lanes - GreenInterval \quad (2)$$

As the downstream conditions improve, defined by an actual occupancy less than the desired value, the ramp flow rate increases. This means that more vehicles can be allowed to enter the mainline and hence the signal timing is updated to allow shorter red times and more frequent green intervals (each of 2 seconds of green). On the other hand, as the downstream conditions worsen, defined by an actual occupancy higher than the desired value, the ramp flow rate is decreased. In order to account for that, the signal timing is updated to allow longer red times and less frequent green intervals.

As the red times become longer because of congested downstream conditions on the mainline, queues start to form on the on-ramps that might spillback on the surface streets. In order to prevent that from happening, queue override strategy is used. Queue detectors were placed at a distance of 60 to 80% of the ramp length, to detect the ramp queues. The queue override strategy is set so that, as the ramp queue reaches the queue detectors' location with an occupancy value of 0.1, the ramp meter traffic signal turns to a continuous green until the ramp queue is flushed. The queue detectors distance was changed as the currently used case, the detectors at the very end of the on-ramps, may not help to prevent the surface streets queue spillbacks totally.

Heuristic Traffic Responsive Feedback Control Strategy: HERO

HERO is a coordinated ramp metering control strategy. The HERO strategy was performed between three sets of two ramps as shown in Figure 3. The selected locations were the only ramps that can be coordinated because of their vicinity to each other. The other locations are spaced apart, which does not allow the coordination to be effective. The HERO strategy coordinates the ramp meter flow rates on at least two successive on-ramps. In the HERO strategy, the on-ramps are first controlled by ALINEA local strategy then as specific traffic conditions are satisfied on the mainline and the on-ramps, the coordination is activated. Figure 4 shows the ramp metering control scheme in HERO or mixed strategy.

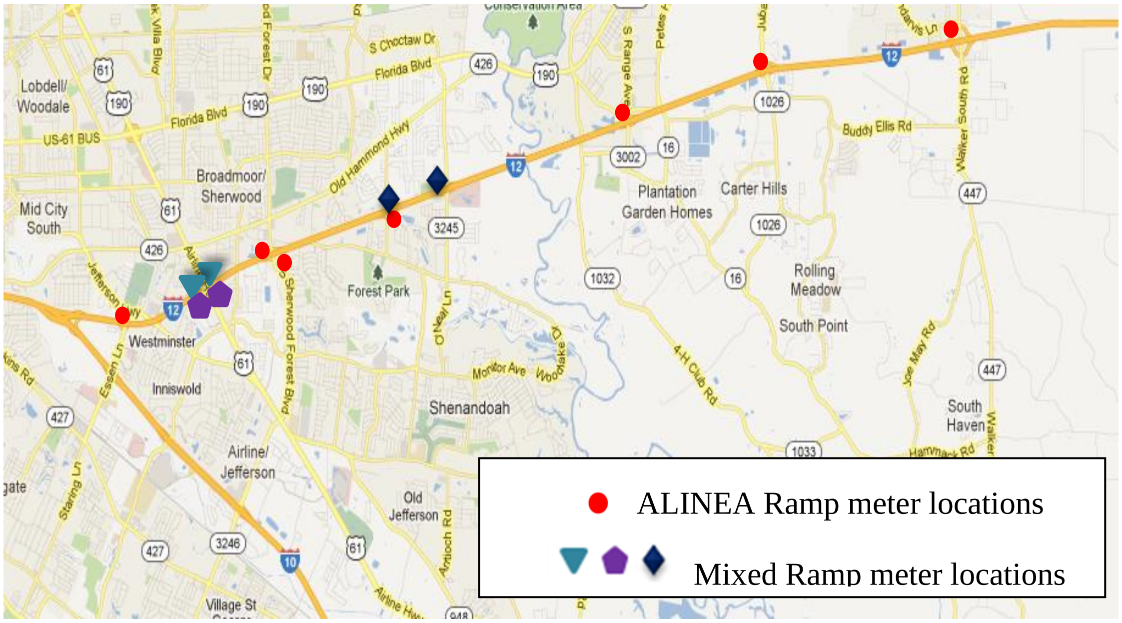


Figure 3
Locations of ramp metering coordination

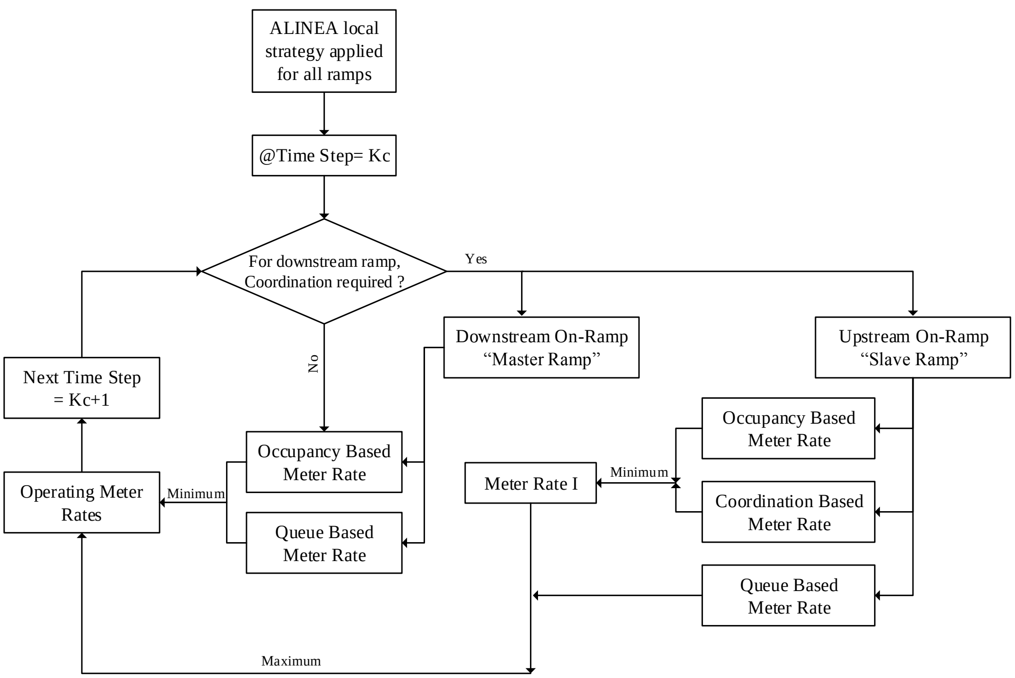


Figure 4
Operation process for mixed ramp metering algorithm

As shown in the figure, the two ramps (where coordination is required) start operating with ALINEA local strategy. The meter flow rate for ALINEA, in the mixed strategy, is calculated as the maximum of two values. The first meter rate is calculated based on the downstream conditions as in equation (1). Whereas, the second meter rate is calculated so as to ensure that the queue length on any ramp does not exceed a predefined maximum value. This is calculated by

$$r(k_c) = -\frac{1}{T_c}[w_{max} - w(k_c)] + d(k_c - 1) \qquad (3)$$

where, T_c is length of the feedback control time steps, w_{max} is the maximum allowed queue length on the ramp, w_o is the actual ramp queue length, and $d$is the ramp demand. Continuously, at the end of each feedback control time step, the traffic conditions downstream of the downstream on-ramp as well as on the downstream on-ramp are checked against the thresholds in the following equations:

$$\frac{w_d}{w_{max}} > Maximum\ threshold \qquad (4)$$

$$O > 0.9 * \hat{O} \qquad (5)$$

where, w_d is the actual queue length on the downstream ramp, w_{max} is the maximum allowed queue length on the downstream ramp, O is the actual occupancy downstream the merging area of the downstream ramp, and $\hat{O}$ is the desired occupancy downstream the merging area of the downstream ramp. If the two conditions are satisfied, the coordination between the two ramps is activated with the downstream ramp treated as the master ramp and the upstream ramp treated as the slave ramp.

For the master ramp, ALINEA rules remain in operation, whereas more restrictions are used for the meter rate of the slave ramp. The meter flow rate of the slave ramp is calculated in two steps. First, the meter rate is calculated as the minimum of the values obtained from equation (1) and the equation below:

$$r_{lc}(k_c) = -\frac{1}{T_c}[w_{min} - w(k_c)] + d(k_c - 1 \qquad (6)$$

where, $w_{min}$is the minimum permissible queue length on the slave ramp. The reason for maintaining a minimum queue on the slave ramp is to allow better traffic conditions at the merging area downstream the master ramp. This can help more vehicles to be discharged from the master ramp. Then, the final meter rate is calculated as the maximum of the values obtained from the first step and equation (4). The minimum permissible queue on the slave ramp is calculated based on the actual and maximum allowed queue values on both the slave and master ramp by:

$$w_{min} = \frac{w_{slave}(k_c)+w_{master}(k_c)}{w_{max,slave}+w_{max,master}} \cdot w_{max,master} \tag{7}$$

While the coordination is active, the traffic conditions on and downstream the master ramp are checked for any improvements using the conditions in the following equations:

$$\frac{W_o}{W_{max}} < deactiviated\ threshold \tag{8}$$

$$O < 0.8 * \hat{O} \tag{9}$$

If these conditions are not satisfied, this means that the coordination is still required. Otherwise, the coordination is deactivated and each ramp starts to operate locally using ALINEA control strategy.

Measures of Performance

The three-ramp metering strategies were evaluated using three performance measures: travel time, speed, and vehicle hours travelled (VHT). The three measures were obtained for each of the tested strategies with the fixed-time control considered as the base case. The different measures were obtained for 20 simulation runs for each strategy in order to account for the randomness effect in the simulation results. The average values over the simulation runs were obtained for each ramp meter location to be used for section-by-section analysis. In addition, the aggregated averaged measures obtained along the entire corridor to be used for corridor-level analysis. Then, comparative statistical analysis at 5% level of significance was performed on each performance measure to find the optimal strategy.

The Analysis of Variance (ANOVA) was performed on each measure of performance over the different ramp metering strategies. This was performed for the calculated measure of performance along the corridor (corridor-level calculated measure of performance) to investigate whether changing the ramp metering strategy would improve that measure significantly. Then, if a significant improvement was found for the entire corridor, further section-by-section analysis was then performed using the measure of performance calculated for each ramp meter location (section-level calculated speed). The section-by-section analysis was performed to investigate the ramp meter locations that benefited the most from each strategy.

The following sections describe the methodology used to compute each measures of performance.

Travel Time

The freeway was divided into smaller segments where each segment included an on-ramp meter location. For each segment, travel time measuring sections were placed in VISSIM simulation models. The travel times for the different strategies were then measured for each vehicle and then the average value was obtained for each section. In addition, the average travel times were aggregated over the entire corridor. The calculations were performed over the ramp meters' periods of operation (6:00-9:00 a.m. for the westbound and 3:00-7:00 p.m. for the eastbound).

Travel Speed

The travel speed for each vehicle was calculated using the measured travel times. Then the average speed for each section was calculated for each ramp meter location. The average speed was also calculated over the entire corridor. The calculations were performed over the ramp meters hours of operation (6:00-9:00 a.m. for the westbound and 3:00-7:00 p.m. for the eastbound).

Vehicle Hours Traveled (VHT)

The VHT was calculated for each strategy by multiplying the throughput by the travel time. The VHT were calculated for each section and aggregated for the entire corridor. The calculations were performed over the ramp meters' hours of operation (6:00-9:00 a.m. for the westbound and 3:00-7:00 p.m. for the eastbound).

DATA COLLECTION AND DESCRIPTION OF TRAFFIC CONDITIONS

Data Collection

In this study, the selected ramp metering strategies were tested using a simulation model for I-12 corridor. The simulation model requires geometric and traffic data to be collected to be built. The geometric data include the number of lanes along the I-12 corridor, the number of lanes on the on-ramps and the off-ramps, and the horizontal alignment of the corridor. These data were obtained using Google Maps. For the number of lanes, the Geaux Wider program web page was used to account for the construction taking place on I-12 that is intended to increase the number of lanes at some sections of the corridor. For the traffic data, speed limits, actual travel time, and traffic volumes were collected. The speed limits information along the corridor as well as on the on-ramps and the off-ramps were obtained from the DOTD webpage. The travel time and traffic volumes data were collected during the operation hours of the ramp meters.

For the traffic volumes, the Advanced Traffic Management Systems (ATMS) software was used to control the cameras mounted on I-12 to record videos for 20 different locations along the I-12 corridor. The video recordings covered all merging (on-ramps) and diverging (off-ramps) locations during the operation hours of the ramp meters (6:00-9:00 a.m. for the westbound and 3:00-7:00 p.m. for the eastbound). Because of the limited number of available cameras, the video recordings were collected over three weekdays (Monday, Tuesday, and Wednesday). Some of the recorded videos were repeated to guarantee incident free data. Manual counts were then performed on the recorded videos which added up to 242 hours of counts. For each location, traffic volumes on the mainline as well as the ramps were counted broken down by 15 minutes. Manual vehicle classification was also performed during the counts to account for the percentage of heavy vehicles in the traffic. A sample of the counts is shown in Table 1. In order to account for that the recordings were obtained over different weekdays, the counted traffic volumes were balanced.

The travel times were obtained from the BlueTOAD data base. The collected travel time data were obtained to cover the periods of the video recordings. Some weekdays did not have enough travel time data because of the sample size issue of the Bluetooth data, resulting in missing travel times for some hours. Therefore, for these specific hours, the travel times were obtained for the same days but in different months. A sample of the collected travel time data is shown in Table 2 and Table 3.

Table 1
Sample of traffic counts

Duration		Mainline		On-Ramp	
From	**To**	**Total # of Vehicles**	**# of Trucks**	**Total # of Vehicles**	**# of Trucks**
3:00 p.m.	3:15 p.m.	1160	113	96	0
3:15 p.m.	3:30 p.m.	1174	83	110	8
3:30 p.m.	3:45 p.m.	1233	105	101	0
3:45 p.m.	4:00 p.m.	1253	30	97	14
4:00 p.m.	4:15 p.m.	1302	90	121	14
4:15 p.m.	4:30 p.m.	1313	120	126	8
4:30 p.m.	4:45 p.m.	1281	60	134	23
4:45 p.m.	5:00 p.m.	1014	83	126	0
5:00 p.m.	5:15 p.m.	1117	53	151	8
5:15 p.m.	5:30 p.m.	1082	90	119	8
5:30 p.m.	5:45 p.m.	1172	60	106	14
5:45 p.m.	6:00 p.m.	1065	30	93	0
6:00 p.m.	6:15 p.m.	1132	90	94	8
6:15 p.m.	6:30 p.m.	980	135	61	23
6:30 p.m.	6:45 p.m.	864	90	75	0
6:45 p.m.	7:00 p.m.	759	98	60	0

Table 2
Sample of Bluetooth data (segment numbers and descriptions)

	PairID	Active	OD	Distance	Direction	From	To	Pair Name
1	799	Y	N	5.7	E	1012	1023	Essen (u1012) to Oneal (u1023)
2	804	Y	N	8.91	E	1012	1014	Essen (u1012) to Range (u1014)
3	1665	Y	N	0.77	E	1012	1019	Essen WB (u1012) to Jefferson EB (u1019)
4	1705	Y	N	1.77	E	1012	1015	Essen WB (u1012) to NB Airline EB (u1015)
5	1701	Y	N	2.96	E	1012	1022	Essen WB (u1012) to Sherwood EB (u1022)
6	1704	Y	N	2.63	E	1012	1021	Essen WB (u1012) to Sherwood WB (u1021)
7	1664	Y	N	0.77	W	1019	1012	Jefferson EB (u1019) to Essen WB (u1012)
8	1104	Y	N	4.13	E	1019	1018	Jefferson EB (u1019) to Millerville EB (u1018)
9	1666	Y	N	0.99	E	1019	1015	Jefferson EB (u1019) to NB Airline EB (u1015)
10	1700	Y	N	2.19	E	1019	1022	Jefferson EB (u1019) to Sherwood EB (u1022)
11	1703	Y	N	1.86	E	1019	1021	Jefferson EB (u1019) to Sherwood WB (u1021)
12	802	Y	N	3.3	E	1016	1017	Juban (u1016) to Walker (u1017)
13	838	Y	N	5.7	W	1016	1023	Juban to O'Neal Westbound (u1016 to u1023)
14	3940	Y	N	6.73	W	1016	1018	Juban WB (u1016) to Millerville WB (u1018)
15	791	Y	N	2.3	W	1016	1014	Juban WB (u1016) to Range WB (u1014)
16	1678	Y	N	3.2	W	1013	1015	Millerville EB (u1013) to NB Airline EB (u1015)
17	1691	Y	N	0.72	E	1013	1023	Millerville EB (u1013) to O'Neal WB (u1023)
18	1669	Y	N	3.83	E	1013	1014	Millerville EB (u1013) to Range WB (u1014)
19	1677	Y	N	2.01	W	1013	1022	Millerville EB (u1013) to Sherwood EB (u1022)

Table 3
Sample of Bluetooth data (travel time data)

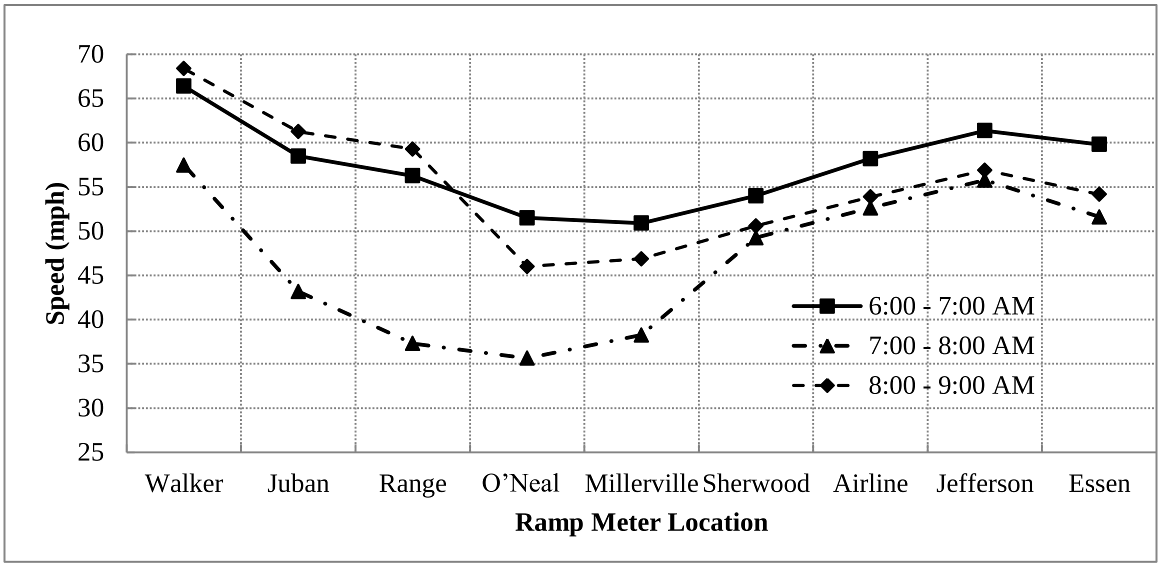
	PairID	TravelTime	DateTime
1	1675	155	2014-11-07 10:30:00
2	1675	156	2014-11-07 10:45:00
3	1675	147	2014-11-07 11:00:00
4	1675	151	2014-11-07 11:15:00
5	1675	154	2014-11-07 11:30:00
6	1675	156	2014-11-07 11:45:00
7	1675	155	2014-11-07 12:00:00
8	1675	149	2014-11-07 12:15:00
9	1675	152	2014-11-07 12:30:00
10	1675	149	2014-11-07 12:45:00
11	1675	153	2014-11-07 13:00:00
12	1675	153	2014-11-07 13:15:00
13	1675	149	2014-11-07 13:30:00
14	1675	147	2014-11-07 13:45:00
15	1675	157	2014-11-07 14:00:00
16	1675	155	2014-11-07 14:15:00
17	1675	152	2014-11-07 14:30:00
18	1675	159	2014-11-07 14:45:00
19	1675	161	2014-11-07 15:00:00

Description of Traffic Conditions

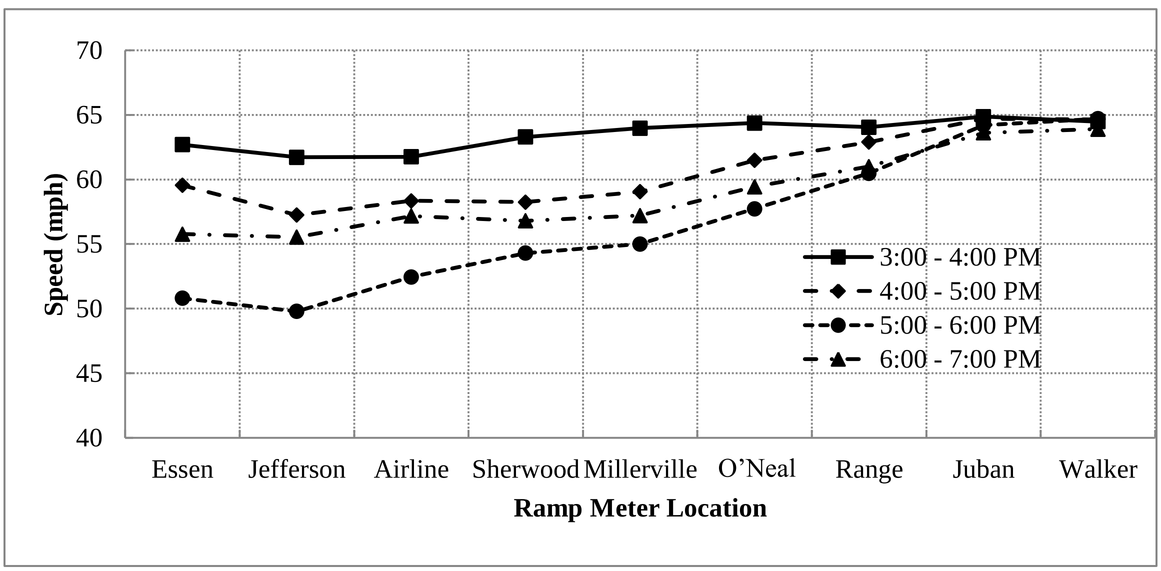
The speed profiles along the I-12 corridor were used to understand the traffic conditions at which the I-12 bounds (eastbound and westbound) are operating. The speed data at the different locations of I-12 that were calculated using the collected travel time data. The speed profiles for the eastbound and westbound directions are shown in Figure 5. For the westbound direction, the speed profiles show that at the beginning of the operating hours of the ramp meters (at 6:00 a.m.), the speed value is higher than 55 mph at most of the ramp meters' locations. The speed drops below 55 mph at only three locations: O'Neal, Millerville, and Sherwood. At 7:00 a.m., the speed drops to below 55 mph almost along the entire westbound direction, and it drops to as low as around 35 mph at Range, O'Neal and Millerville. Then, by the end of the ramp meters' hours of operation, the speeds go up to more than 50 mph, except at O'Neal and Millerville. These changes in the speed show that the westbound direction suffers from bottlenecks at different locations that cause the high drops in the travel speed. The most affected locations, according to the speed profiles, are O'Neal and Millerville.

On the other hand, for the eastbound direction, the speed profiles show that with the beginning of the operating hours of the ramp meters (at 3:00 p.m.), the speed value higher than 60 mph along the entire corridor. The speed also goes up to as high as 65 mph at some locations including Walker and Juban. At 4:00 p.m., the speed starts to drop to below 60 mph at some locations starting from Essen to Millerville. Then, at 5:00 p.m., the speeds drop to its lowest values during the rush hours (3:00 to 7:00 p.m.), but it remains higher than 50 mph along the entire corridor. By the end of the rush hours, at 6:00 p.m., the speed goes up again to above 55 mph along the entire corridor. The speed profiles over the four hours of the ramp meters operation show that the speed drops take place starting from Essen Lane. Then, the speed starts to go up as the vehicles travel towards Juban and Walker, where the speeds are maintained all the time at 63 to 65 mph.

The discussion of the speed profiles shows that, unlike the westbound direction, there are no bottlenecks that can be detected on the eastbound direction, especially with the smooth speed profiles that are all the time higher than 50 mph. This shows that while the westbound suffers from bottlenecks at some locations, the traffic on the eastbound is free flowing along the entire corridor.



(a) Westbound



(b) Eastbound

Figure 5
Section-by-section average speed results (sec/veh)

I-12 SIMULATION MODEL

The microsimulation VISSIM software was chosen to test the selected ramp metering strategies on I-12 because of its flexibility in networks' coding and simulation. In addition, the availability of 10 licenses of VISSIM software at the ITS lab, at the LTRC, helped in making the decision to choose VISSIM as the assessment tool in this study. With its VAP interface, VISSIM provided the capability to simulate Active Traffic Management (ATM) applications such as ramp metering. In this section, the I-12 model coding and calibration are discussed.

I-12 Corridor Model Encoding

To encode the I-12 corridor in VISSIM, the geometric model was first built using scaled high definition up-to-date images obtained from Google Maps. The geometric data collected about the number of lanes along the corridor and on the on-ramps and off-ramps and the construction work were accounted for in the model. Speed limits were then assigned to the I-12 main stream as well as its on and off-ramps using the desired speed distributions feature in VISSIM. Using the balanced and classified traffic volumes counted from the collected video recordings, the vehicle compositions and traffic flows were defined in the I-12 simulation model.

The ramp meters and the current detectors' locations were identified using as-built-footprints provided by Stantec Consultancy Company. The required signal heads along with the detectors for queue override were placed on the on-ramps in the simulation model according to the information obtained from the footprints. Additional detectors were then placed according to the requirements of each of the tested ramp metering strategy.

The VAP interface was used to develop the required programs for the three ramp metering strategies: fixed-time, which served as the base case, ALINEA that represented the local ramp metering strategy, and Mixed, which included the coordinated and the local ramp metering strategies, as shown in Figure 3. The queue override strategy was also programmed using the VAP interface to work with the fixed-time strategy, to represent the current in-situ situation on I-12, and with ALINEA. For the fixed-time strategy, the queue override was activated whenever the vehicles on the ramp spill back until they reach the very end of the ramp. The queues in this case were detected using video detection by cameras mounted at the end of each ramp. This was not the case for ALINEA strategy, as the queue detection was performed differently as discussed in the research methodology.

After the network was encoded and the different strategies were programmed, the researchers calibrated the simulation model. The simulation model calibration was required to guarantee that the I-12 simulation model operates at conditions as close as possible to the actual conditions. Two main performance measures were used for the calibration: traffic flows and speed profiles. In order to obtain these values from the simulation model, data collection points and travel time sections were placed along the I-12 corridor model as well as at the entrances of the on-ramps and the exits of the off-ramps. The values of each measure were obtained from 20 simulation runs for the fixed-time strategy with the queue override strategy (the base case). The results were also obtained for different simulation scenarios by changing the car following and lane changing parameters of the simulation model.

Simulation Model Calibration

The simulation model calibration was performed through dealing with three main groups of parameters: the car following parameters, the lane changing parameters, and the routing decisions. Each group of parameters is discussed in the following sections.

Car Following Parameters

The car following behavior in VISSIM is simulated based on two main car following models: the Wiedemann99 and the Wiedemann74. The Wiedemann99 model accounts for modeling the car following behavior on freeways while the Wiedemann74 model accounts for the car following behavior on the urban/arterial roads. For the I-12 study corridor, the car following behavior was calibrated considering the freeway Wiedemann99 model.

The calibration was performed by changing several parameters that are shown in Figure 6. Different values were tested for three car following parameters including the look ahead distance, CC0, CC1, and CC2. The look ahead distance parameters controlled the smoothness of the merging and diverging maneuvers by providing either longer or shorter look ahead distances. Only the number of observed vehicles was changed to either 3 or 4 for some of the merging and diverging areas. The remaining parameters that controlled the car following behavior are called the 10 Cs; a brief description to each parameter is shown in Table 4. Only three parameters were calibrated which include CC0, CC1, and CC2 as they had the highest influence on the lane capacity and the car following behavior. CC0 is the desired standstill gap distance between two vehicles; CC1 is the desired headway time between the two moving vehicles; and, CC2 is an additional threshold distance the following vehicle can keep with leading one in addition to the standstill distance before it starts to accelerate to decrease gap distance back to CC1. These three parameters control the desired safety distance during standstill and moving conditions and, in turn, control the lane capacity.

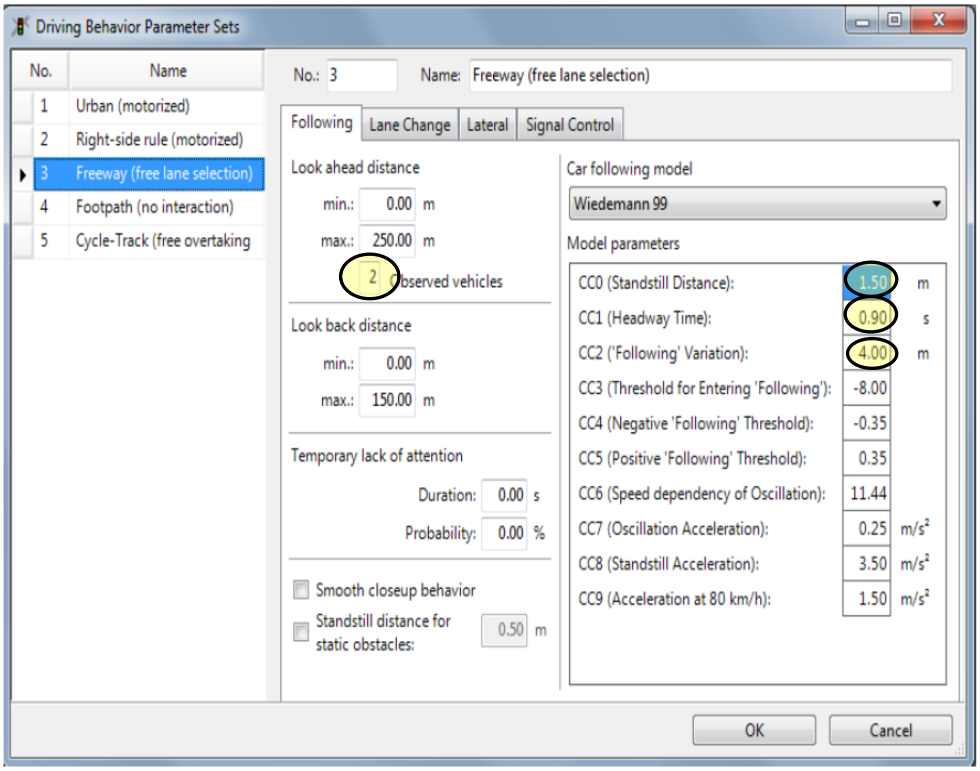


Figure 6
Parameters of Wiedemann99 car-following model in VISSIM 6

Table 4
Wiedemann99 parameters *[34]*

Category	VISSIM Code	Description	Default Value
Thresholds for Dx	CC0	**Standstill distance:** Desired distance between lead and following vehicle at v = 0 mph	4.92 ft
	CC1	**Headway Time:** Desired time in seconds between lead and following vehicle	0.90 sec
	CC2	**Following Variation:** Additional distance over safety distance that a vehicle requires	13.12 ft
	CC3	**Threshold for Entering 'Following' State:** Time in seconds before a vehicle starts to decelerate to reach safety distance (negative)	-8.00 sec
Thresholds for Dv	CC4	**Negative 'Following' Threshold:** Specifies variation in speed between lead and following vehicle	0.35 ft/s
	CC5	**Positive 'Following Threshold:** Specifies variation in speed between lead and following vehicle	0.35 ft/s
	CC6	**Speed Dependency of Oscillation:** Influence of distance on speed oscillation	11.44
Acceleration Rates	CC7	**Oscillation Acceleration:** Acceleration during the oscillation process	0.82 ft/s^2
	CC8	**Standstill Acceleration:** Desired acceleration starting from standstill	11.48 ft/s^2
	CC9	**Acceleration at 50 mph:** Desired acceleration at 50 mph	4.92 ft/s^2

Lane Changing Parameters

The Willmann and Sparmann-1978 model was used in VISSIM to control the lane changing behavior of vehicles. The lane changing parameters that were calibrated included the deceleration rates and the cooperative lane changing; see Figure 7. These parameters determined the way vehicles interact during lane change maneuvers.

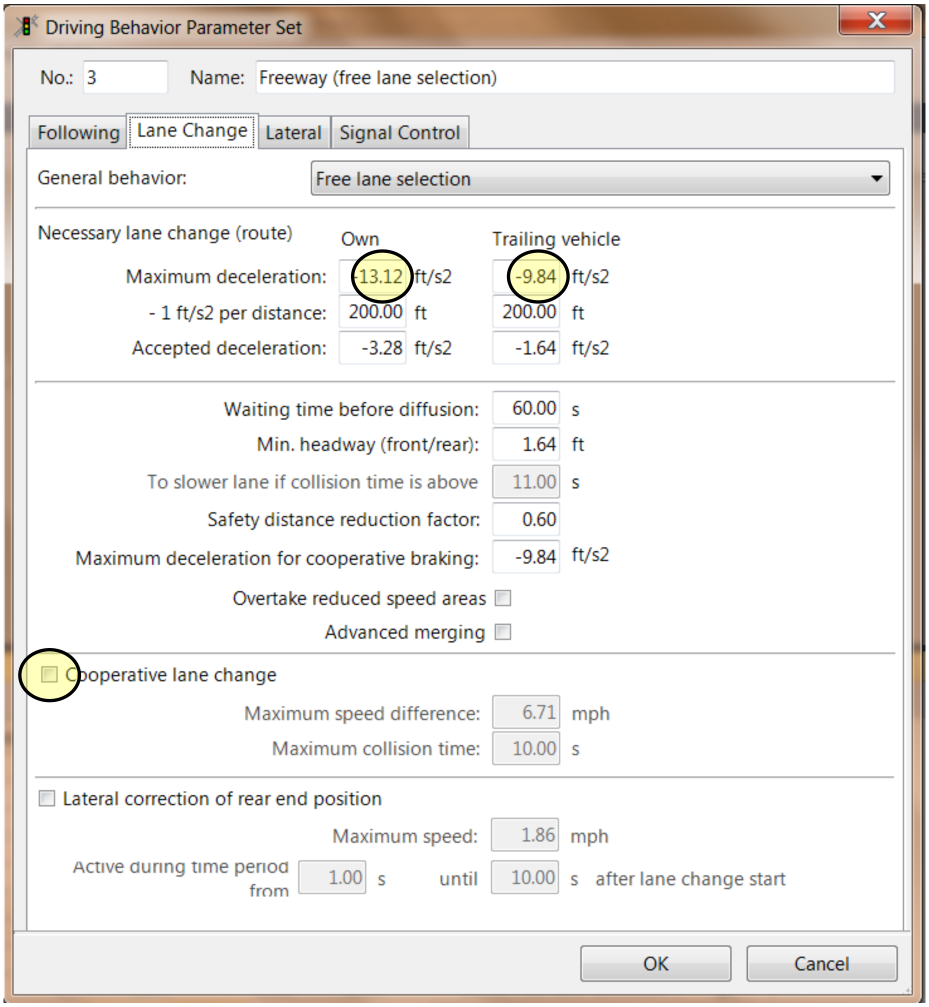


Figure 7
Parameters of Wiedemann and Reiter (1992) lane changing model in VISSIM

Lane Changing Distance and Routing Decision Points

The lane changing distance determines where a lane changing decision is performed at the connectors' locations. The routing decision points represented where a merging and/or a diverging decision is made in the network. Figure 8 shows the lane changing distance parameter in VISSIM. These two parameters helped, in addition to the lane changing parameter, to control the smoothness of the merging and diverging maneuvers at the on-ramps and off-ramps locations, respectively.

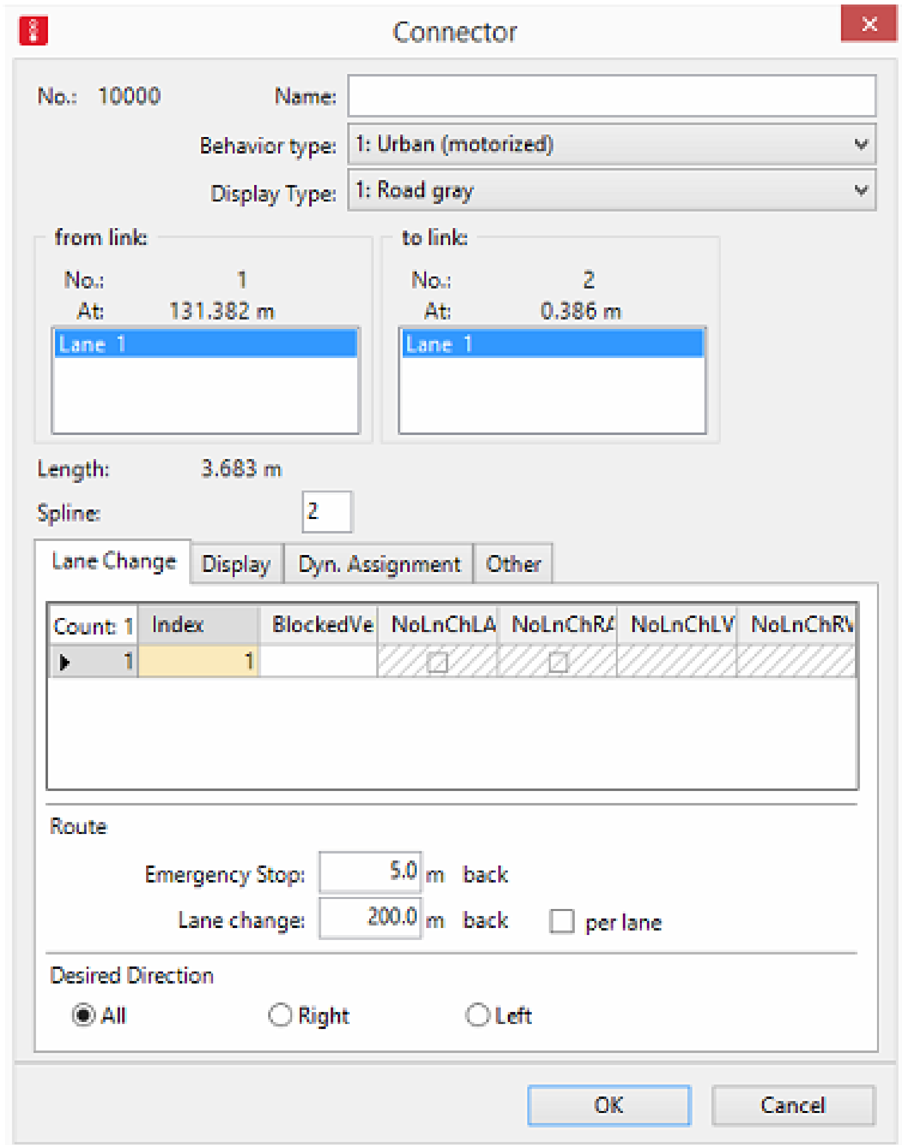


Figure 8
Parameters available for editing for each individual connector

Calibration of Parameters

The different parameters were changed in several simulation runs until they were calibrated. The main objective of the calibration was to make the I-12 simulation model operate at traffic conditions that were as close as possible to the actual conditions. The calibration runs were performed considering fixed-time ramp metering strategy and the queue override strategy with the queue detectors placed at the very end of the on-ramps.

For the car following parameters, the selected three parameters were changed over different simulation trials, as shown in Table 5. These values were selected such that realistic traffic conditions could be obtained. The values were also selected based on the recommended values by Mai et al. *[35]*.

Table 5
Driving behaviors used in this study

Driving behavior	Observed vehicles	C0	C1	C2
1	2	4.9	0.9	13.1
2	3	4.9	1.1	13.1
3	4	6.0	1.2	13.1
4	4	4.9	0.9	13.1
5	4	5.5	1.5	20.0
6	2	5.5	1.3	20.0
7	3	5.5	1.5	20.0
8	4	4.9	0.85	6.6

In some simulation runs, while calibrating the car following parameters, some vehicles experienced unexpected stopping at the diverging locations in the vicinity of the off-ramps. This was due to that those vehicles failing to perform the required lane changing maneuvers to reach the exit, causing unrealistic congestion. These unexpected stops resulted in high congestions upstream the off-ramps locations. In order to overcome this problem, the lane changing parameters were recalibrated. The cooperative lane changing was activated; in addition, the deceleration rates for both the lane changing vehicle and the trailing vehicle were set to 25 ft/sec^2. Using the cooperative lane changing property allowed the trailing vehicles to slow down in order to make wider gaps available for the vehicles performing the lane changing maneuvers. Despite the selected deceleration rate value was not conforming to the recommended values by Mai et al., it was able with the help of the cooperative lane changing feature to resolve the unexpected stops issue *[35]*.

Figure 9 shows the traffic volumes for the approved trial over one hour of the ramp meters' operation time (from 6:00 to 7:00 a.m.) for the westbound direction. Similarly, Figure 10 shows the traffic volumes for the approved calibration trial over one hour of the ramp meters' operation time (from 3:00 to 4:00 p.m.) for the eastbound direction. The results show that the difference between the approved trial's traffic volumes and the actual traffic volumes do not exceed 4.0% for the westbound direction and 2.0 % for the eastbound direction. In most cases, these differences were as low as 0% along the entire corridor. Similar results were obtained for the speed profiles on the eastbound and the westbound directions. Figure 11 shows the speed profile values for the approved calibration trial over one hour of the ramp meters' operation time (from 8:00 to 9:00 a.m.) for the westbound direction. Similarly, Figure 12 shows the speed the profile values for the approved calibration trial over one hour of the ramp meters' operation time (from 4:00 to 5:00 p.m.) for the eastbound direction. The results show that while the maximum speed difference between the approved trial and actual values were 15% for the westbound direction and 14% for the eastbound direction, the average difference was as low as 3% for both directions. In summary, the calibrated results give a good indicator that the I-12 simulation model operates at traffic conditions that have a very close pattern to the in-situ conditions.

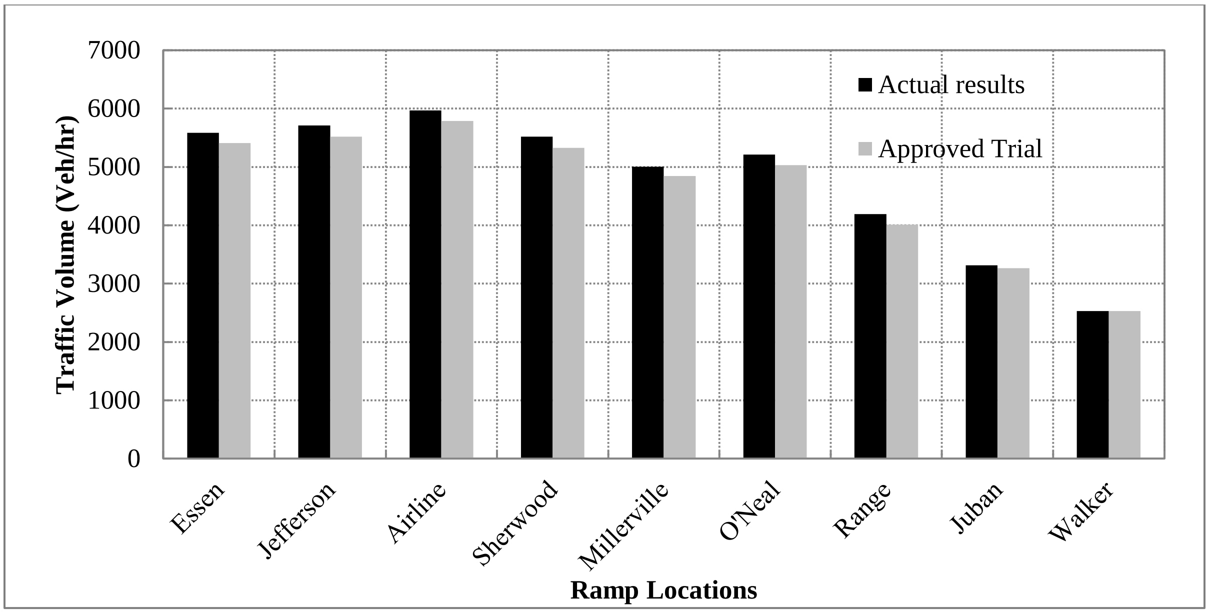


Figure 9
Final simulation model hourly volumes compared to actual ones for the westbound direction

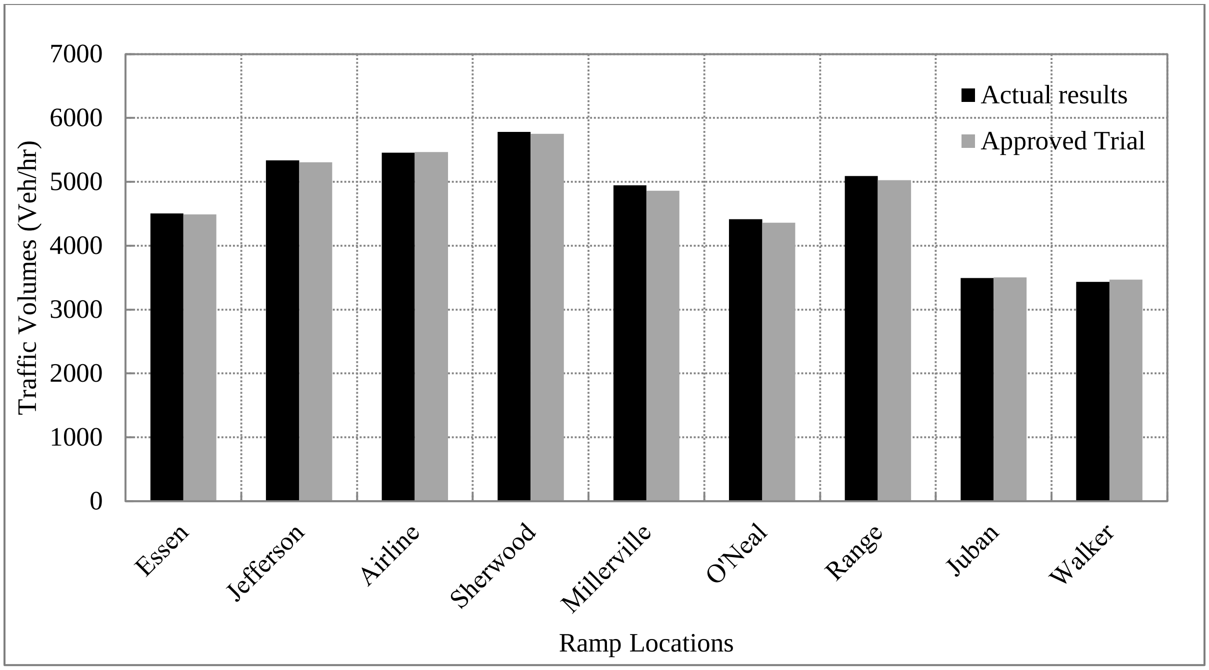


Figure 10
Final simulation model hourly volumes compared to actual ones for the eastbound direction

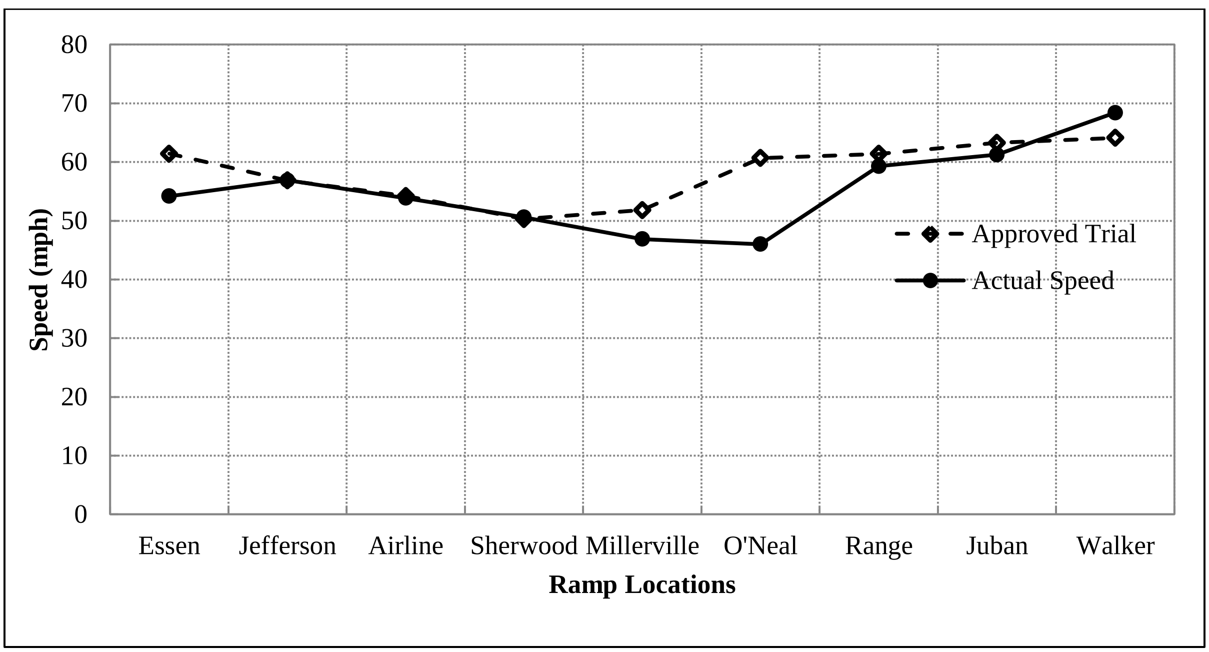


Figure 11
Actual speed profile along the I-12 along with the selected model results and other trials for the westbound direction

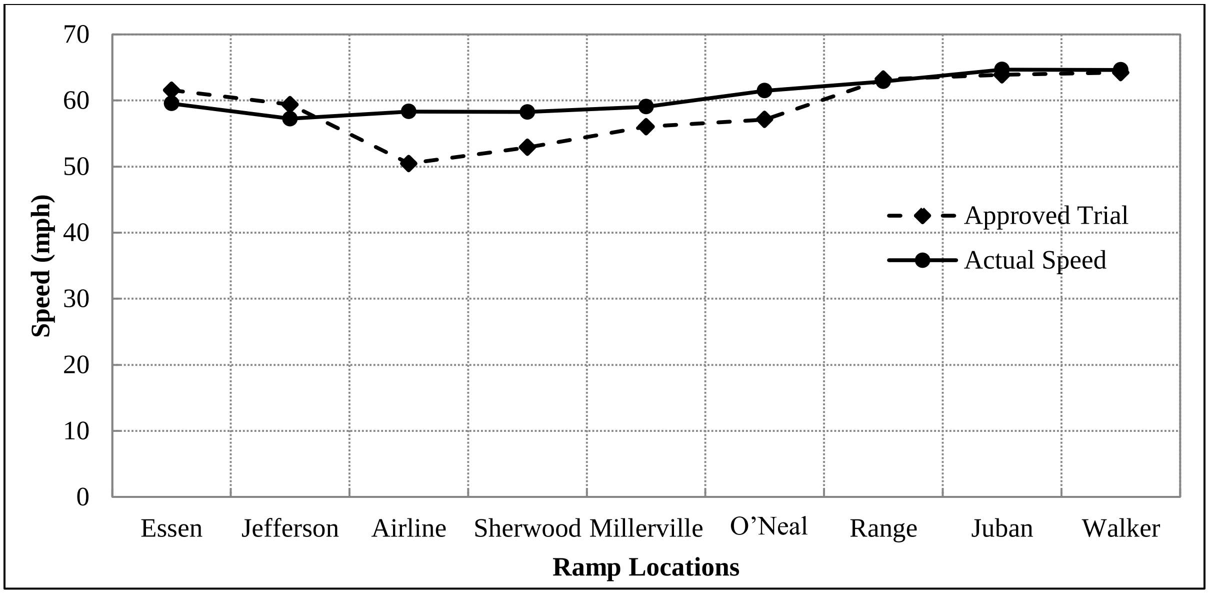


Figure 12
Actual speed profile along the I-12 along with the selected model results and other trials for the eastbound direction

Calibrating ALINEA Parameters

The ALINEA strategy operated based on three main parameters: the optimum occupancy on the mainline downstream the on-ramp, the downstream detector distance at which the optimum occupancy is required, and the gain factor (KR). While some of these parameters have recommended values in the literature, they are site-specific. Therefore, the three parameters were calibrated in order to find the optimal values that can achieve superior improvements in the traffic conditions on I-12. As such, different values were tested for each parameter. More specifically, the optimum occupancy parameter was set to 0.1, 0.2, 0.3, and 0.4; the gain factor KR was set to 60, 70, and 80 Veh/hr; and, finally, the downstream detector distance was set to 200, 500, and 1000 feet downstream the on-ramp.

Using the selected values for the different parameters, 20 simulation runs were performed using the calibrated I-12 simulation model on each of 36 combinations for ALINEA. For each simulation run, the three performance measures (the speed, travel time, and VHT) were obtained. The results were obtained throughout the ramp meters hours of operation, 6:00 to 9:00 a.m. for the westbound and 3:00 to 7:00 p.m. for the eastbound.

The results of the 36 combinations were comparatively evaluated using Multivariate Analysis of Variance (MANOVA) test. MANOVA analysis was performed with the speed, travel time, and VHT treated as the dependent variables while the three ALINEA parameters were treated as the independent variables. Then, for the ALINEA parameters that were significantly affecting the performance measures, the Post Hoc test (Tukey) was conducted to identify the optimal combination of parameters. Both the MANOVA and the Post Hoc analysis were performed at 95% level of confidence; see Appendix B.

The results indicated that, for the eastbound direction, the gain factor and the optimum occupancy had no significant effect on the dependent variables. Although, the detector's distance had the highest impact on the dependent variables, its effect was statistically not significant. Therefore, for the eastbound, the optimal values of ALINEA were selected based on the field conditions. The simulation results showed that the downstream actual occupancy was in the range of 0.3 to 0.4 most of the time. The simulation model showed that these values take place within distance of 500 to 1000 ft. downstream the on-ramps. As such, in order to detect and improve the traffic conditions on the mainline, a detector distance of 1000 ft. with an optimum occupancy value of 0.2 were selected. For the gain factor, the recommended value in the literature, 70 veh/hr, was used.

Similarly, for the westbound direction, the gain factor and the optimum occupancy had no significant effect on the dependent variables. However, the detector's distance was affecting the performance measures significantly. As such, further Post Hoc tests were performed to identify the optimal value. The results indicated that detector's distance value of 500 ft. achieved the most significant improvements in the speed, travel time, and VHT values. For the optimum occupancy, similar to the eastbound direction and for the same reason, a value of 0.2 was selected. For the gain factor, the recommended value in the literature, 70 veh/hr, was used.

DISCUSSION OF RESULTS

Travel Time

Using the simulation results, the average travel times were calculated over the entire I-12 corridor for the eastbound and westbound directions. The travel times for the different tested strategies were calculated as average values calculated for each section in the corridor (each section is defined by a ramp meter location). In addition, the average travel times were also aggregated over the entire corridor. The calculations were performed over the ramp meters' period of operation (6:00-9:00 a.m., for the westbound, and 3:00-7:00 p.m., for the eastbound). In the following sections, a discussion for the corridor level travel times and the section-by-section level travel times is presented.

Corridor Level Analysis

The resulting average travel times for a vehicle to travel over the entire corridor are shown in Table 6 for the different ramp metering strategies. For the eastbound, the table shows that the travel time for the mixed ramp metering control is less than that for the fixed-time control by around 6 seconds. The table shows also that the travel time for the ALINEA is less than that of the fixed-time control by around 2 seconds. These results do not show a practical significance in the travel time improvement for the eastbound direction. On the other hand, for the westbound direction, the ALINEA local ramp metering strategy reduced the travel time by around 20 seconds when compared to the current fixed-time control. Whereas, for the mixed control the travel time was reduced by around 40 seconds which is practically more significant than the ALINEA local control case. The table shows also that the travel times for the eastbound direction are less than those for the westbound direction. The reason for that is that the eastbound is already free flowing which explains why there was no significant practical improvement in the travel times for the eastbound direction.

Table 6
Average travel time results over the corridor

Strategy	Travel Time (sec/veh)	
	Eastbound	Westbound
Mixed	986	1166
ALINEA	990	1187
Fixed-time	992	1206

Further comparative statistical Analysis of Variances (ANOVA) was performed between the different ramp metering strategies using both the sectional travel time information and the aggregated corridor travel time information. The analysis was performed at 5% level of significance to investigate the statistical significance of the travel time reductions caused by each strategy. The ANOVA test results for the corridor level are shown in Table 7. The results show that there was no significant change in the travel time between the different strategies for the eastbound direction with a p-vale of 0.432. This was expected as this direction is already free flowing as shown in the speed profiles for the current traffic conditions in Figure 12. Whereas, for the westbound direction, the table shows that the travel time differences were statistically significant for both the ALINEA and the mixed strategies with a p-value of 0.001.

Table 7
Comparative ANOVA test results for the different ramp metering strategies

Direction	Level of analysis	Sum of Squares	df	Mean Square	F	P-value
Eastbound	Between Strategies	420.889	2	210.445	.852	.432
	Within Strategies	14070.800	57	246.856		
	Total	14491.689	59			
Westbound	Between Strategies	15865.782	2	7932.891	8.378	.001
	Within Strategies	53972.516	57	946.886		
	Total	69838.297	59			

For the eastbound direction, no further analysis is required because there were no statistically significant differences found in the travel time values. Whereas, for the westbound direction, to determine the strategy with the lowest travel times, Post Hoc tests (Tukey) were performed. The results in Table 8 show that no significant change in the travel time values can be found between the fixed-time and the ALINEA ramp metering strategies. Same results were found between the ALINEA and the mixed ramp metering strategies. When comparing the mixed to the fixed-time strategies, the results showed that the travel times for the mixed ramp metering strategy were significantly less than those for the fixed-time strategy.

Table 8
Post Hoc Tukey test results for the different ramp metering strategies

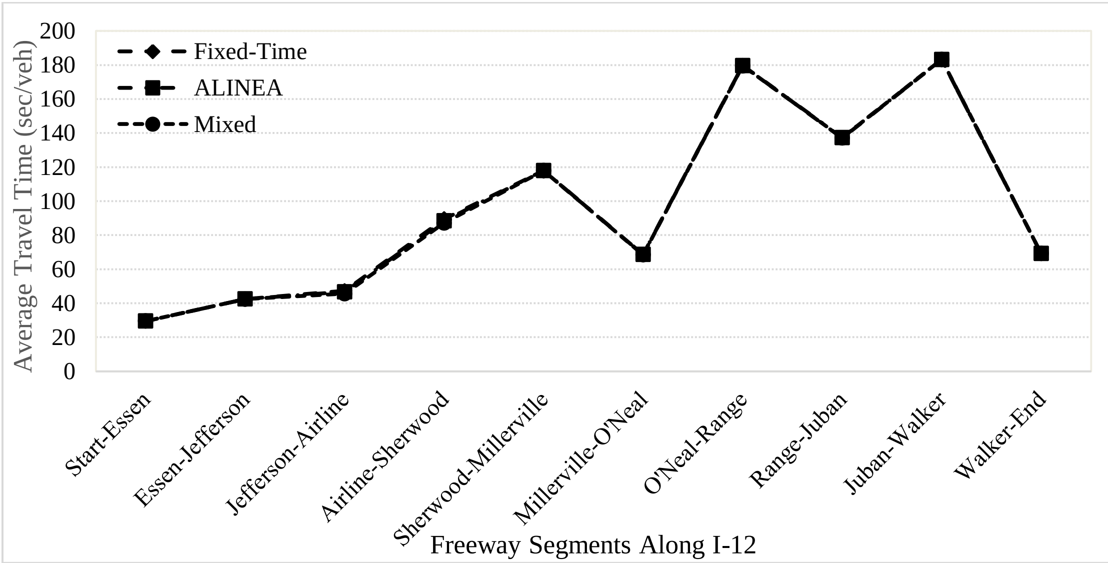
Direction	(I) Strategy	(J) Strategy	Mean Difference (I-J)	Std. Error	P-value	95% Confidence Interval	
						Lower Bound	Upper Bound
Westbound	Fixed Control	ALINEA	19.00000	9.73081	.134	-4.4164	42.4164
		Mixed	39.81804*	9.73081	.000	16.4016	63.2344
	ALINEA	Fixed Control	-19.00000	9.73081	.134	-42.4164	4.4164
		Mixed	20.81804	9.73081	.091	-2.5984	44.2344
	Mixed	Fixed Control	-39.81804*	9.73081	.000	-63.2344	-16.4016
		ALINEA	-20.81804	9.73081	.091	-44.2344	2.5984

* indicates that the difference is statistically significant.

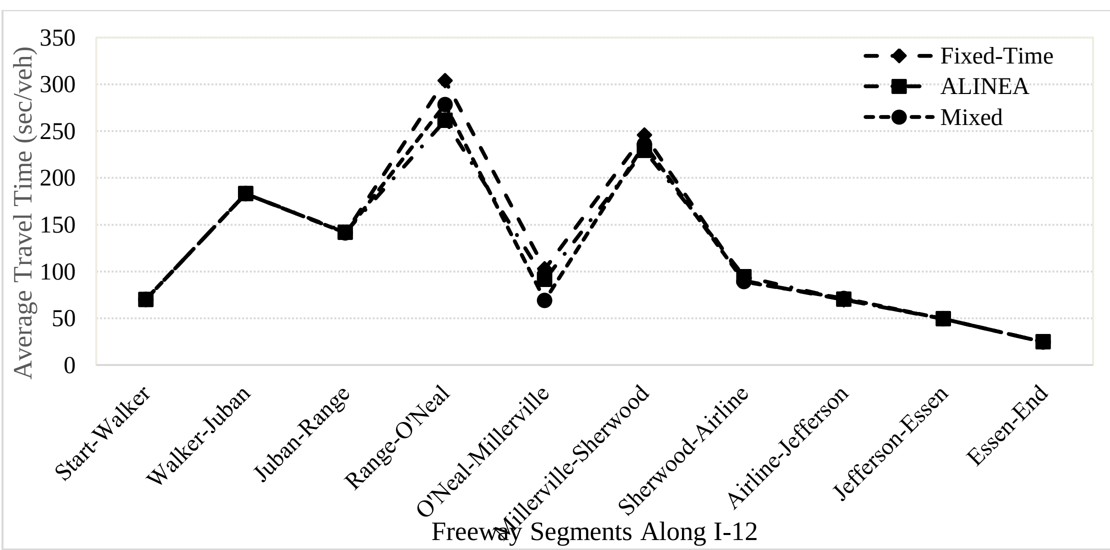
Section Level Analysis

The section level analysis was performed to show more detailed section-by-section results for the impact of the different strategies, see Appendix B. The section-by-section travel times show the ramp meter locations that benefited the most from each ramp metering strategy for each direction. The travel time values for each section is shown in Figure 13. The figure shows that, for the eastbound direction, both the mixed and the ALINEA ramp metering strategies did not show any improvement in the travel time values that can be noticed at any of the ramp meter locations; see Figure 13-a. On the other hand, for the westbound direction, only three sections showed significant improvement in the travel time values when implementing the mixed and the ALINEA ramp metering strategies. As shown in Figure 13-b, these sections include the ramp meters that control the traffic between Range to O'Neal, O'Neal to Millerville, and Millerville to Sherwood.

The travel time improvements shown in Figure 13-b were further investigated statistically using Post Hoc pairwise Tukey test. The statistical analysis results are shown in Table 9. The table shows that, for the section between Range and O'Neal, while there was no significant change in the travel time between the mixed and the ALINEA strategies, both of these strategies showed significant improvement in the travel times when compared to the fixed-time control. For the section between O'Neal and Millerville, the ALINEA ramp metering strategy did not show significant improvement in the travel time; whereas, the mixed control significantly reduced the travel time values when compared to the fixed-time control. For the section between Millerville and Sherwood, despite the mean travel times for the ALINEA and the mixed control strategies were less than that for the fixed-time control, the differences in the travel times were not statistically significant.



(a) Eastbound Direction



(b) Westbound Direction

Figure 13
Section-by-section average travel time results (sec/veh)

Table 9
Section-by-section Post Hoc Tukey test results for the different ramp metering strategies

Dependent Variable	(I) Strategy	(J) Strategy	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Range-O'Neal	Fixed Control	ALINEA	42.62919*	8.62576	.000	21.8720	63.3864
		Mixed	25.73510*	8.62576	.011	4.9779	46.4923
	ALINEA	Fixed Control	-42.62919*	8.62576	.000	-63.3864	-21.8720
		Mixed	-16.89409	8.62576	.132	-37.6513	3.8631
	Mixed	Fixed Control	-25.73510*	8.62576	.011	-46.4923	-4.9779
		ALINEA	16.89409	8.62576	.132	-3.8631	37.6513
O'Neal-Millerville	Fixed Control	ALINEA	11.27422	8.33900	.373	-8.7929	31.3413
		Mixed	33.72709*	8.33900	.000	13.6600	53.7942
	ALINEA	Fixed Control	-11.27422	8.33900	.373	-31.3413	8.7929
		Mixed	22.45286*	8.33900	.025	2.3857	42.5200
	Mixed	Fixed Control	-33.72709*	8.33900	.000	-53.7942	-13.6600
		ALINEA	-22.45286*	8.33900	.025	-42.5200	-2.3857
Millerville-Sherwood	Fixed Control	ALINEA	16.47363	7.41610	.076	-1.3726	34.3199
		Mixed	9.91505	7.41610	.381	-7.9312	27.7613
	ALINEA	Fixed Control	-16.47363	7.41610	.076	-34.3199	1.3726
		Mixed	-6.55858	7.41610	.652	-24.4048	11.2877
	Mixed	Fixed Control	-9.91505	7.41610	.381	-27.7613	7.9312
		ALINEA	6.55858	7.41610	.652	-11.2877	24.4048

Speed

Similarly, the travel speeds were calculated and averaged over the entire I-12 corridor for the eastbound and westbound directions using the simulation results. The operational speed for the different ramp metering strategies were calculated for each ramp meter location along the corridor. The speed was also calculated using aggregated data for the entire corridor. The speed values were calculated over the ramp meters' operation periods (6:00-9:00 a.m., for the westbound, and 3:00-7:00 p.m., for the eastbound). In the following sections, a discussion for the corridor level speeds and the section-by-section speeds is presented.

Corridor Level Analysis

The estimated average travel speeds over the entire corridor are shown in Table 10 for the different ramp metering strategies. For the eastbound direction, the results show that the average operating speed remains almost the same at 59 mph under the three tested strategies. These results do not show any improvement for the corridor operating speed regardless the type of ramp metering strategies. While for the westbound direction, the ALINEA strategy shows a slight increase of speed from 48.7 mph for the fixed-time strategy to 49.5 mph. For the mixed control strategy, the operating speed increased to around 50.4 mph. The table also shows that the resulting speeds for the eastbound direction are more than those of the westbound direction, which is related to the fact that the eastbound direction is operating at free flow conditions.

Table 10
Average speed results over the corridor

Strategy	Speed (mph)	
	Eastbound	Westbound
Fixed-time	59.0	48.7
ALINEA	59.2	49.5
Mixed	59.4	50.4

Further comparative statistical ANOVA was performed between the different ramp metering strategies using both the sectional speed information and the aggregated corridor speed information. The analysis was performed at 5% level of significance to investigate the statistical significance of the travel time reductions caused by each strategy. The ANOVA test results for the corridor level are shown in Table 11. The results show that there was no significant change in the operating speed between the different strategies for the eastbound direction with a p-vale of 0.401. Whereas, for the westbound direction, the table shows that the differences in the operating speed were statistically significant for both the ALINEA and the mixed strategies with a p-value of 0.001.

Table 11
Comparative ANOVA test results for the different ramp metering strategies (speed)

Direction	Level of analysis	Sum of Squares	df	Mean Square	F	P-value
Eastbound	Between Strategies	1.493	2	.746	.929	.401
	Within Strategies	45.782	57	.803		
	Total	47.275	59			
Westbound	Between Strategies	26.917	2	13.458	7.707	.001
	Within Strategies	99.536	57	1.746		
	Total	126.453	59			

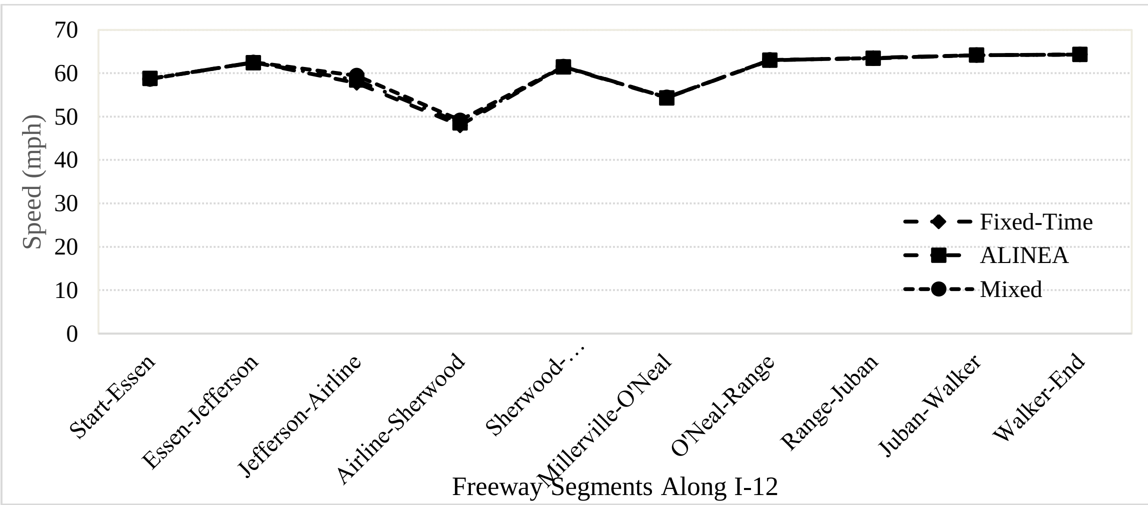
For the eastbound direction, no further analysis is required because there were no statistically significant differences found in the speed values. Whereas, for the westbound direction, to determine the strategy with the highest improvement in the operating speeds, Post Hoc tests (Tukey) was performed. The results in Table 12 shows that there was no significant change in the operating speed values between the fixed-time and the ALINEA ramp metering strategies. Same results were found between the ALINEA and the mixed ramp metering strategies. However, when comparing the mixed to the fixed-time strategy, the results showed that the mixed ramp metering strategy significantly improved the operating speed with a p value of 0.001.

Table 12
Post Hoc Tukey test results for the different ramp metering strategies (speed)

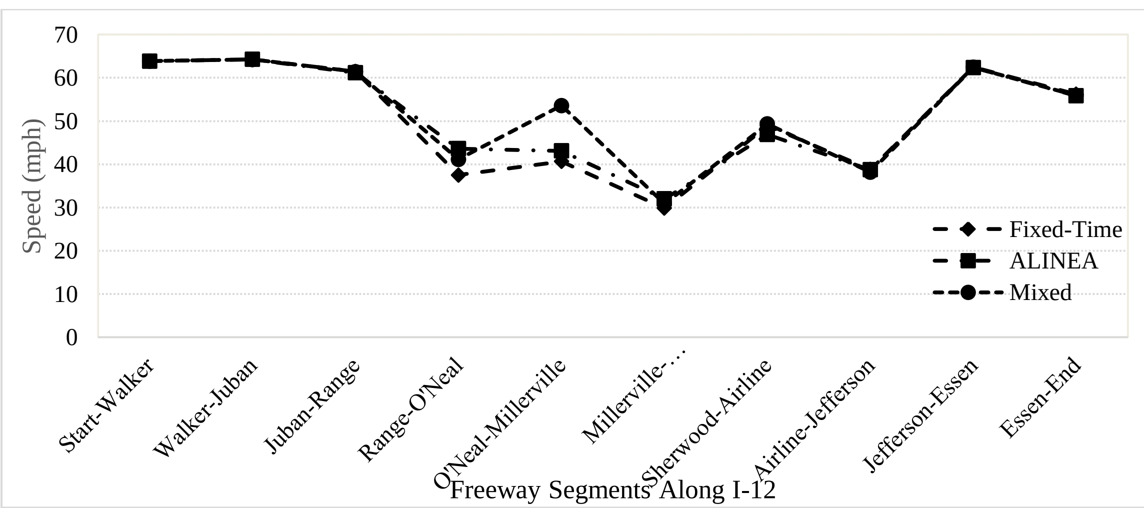
Direction	(I) Strategy	(J) Strategy	Mean Difference (I-J)	Std. Error	P-value	95% Confidence Interval	
						Lower Bound	Upper Bound
Westbound	Fixed Control	ALINEA	-.71591	.41788	.209	-1.7215	.2897
		Mixed	-1.63637*	.41788	.001	-2.6420	-.6308
	ALINEA	Fixed Control	.71591	.41788	.209	-.2897	1.7215
		Mixed	-.92046	.41788	.079	-1.9261	.0851
	Mixed	Fixed Control	1.63637*	.41788	.001	.6308	2.6420
		ALINEA	.92046	.41788	.079	-.0851	1.9261

Section Level Speeds

The section level analysis was performed to show more detailed section-by-section results for the impact of the different strategies; see Appendix B. The section-by-section speed values show the ramp meter locations that benefited the most from each ramp metering strategy for each direction. The speed values for each section are shown in Figure 14. The figure shows that, for the eastbound direction, both the mixed and the ALINEA ramp metering strategies did not show any improvement in the speed values that can be noticed at any of the ramp meter locations; see Figure 14-a. On the other hand, for the westbound direction, only two sections showed significant improvement in the operating speed values when implementing the mixed and the ALINEA ramp metering strategies. As shown in Figure 14-b, these sections include the ramp meters that control the traffic between Range to O'Neal and O'Neal to Millerville.



(a) Eastbound Direction



(b) Westbound Direction

Figure 14
Section-by-section average speed results (sec/veh)

The improvements in the operating speed shown in Figure 14-b were further investigated statistically using the Post Hoc pairwise Tukey test. The statistical analysis results are shown in Table 13. The table shows that, for the section between Range and O'Neal, while there was no significant change in speeds between the mixed and the ALINEA strategies, both of these strategies showed significant improvement in the speed when compared to the fixed-time control. For the section between O'Neal and Millerville, only the mixed control strategy showed a significant increase in the speed values when compared to the fixed-time and ALINEA control strategies.

Table 13
Section-by-section Post Hoc Tukey test results for the different ramp metering strategies

Dependent Variable	(I) Strategy	(J) Strategy	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Range-O'Neal	Fixed Control	ALINEA	-6.10826*	1.18055	.000	-8.9492	-3.2674
		Mixed	-3.64080*	1.18055	.009	-6.4817	-.7999
	ALINEA	Fixed Control	6.10826*	1.18055	.000	3.2674	8.9492
		Mixed	2.46746	1.18055	.101	-.3734	5.3084
	Mixed	Fixed Control	3.64080*	1.18055	.009	.7999	6.4817
		ALINEA	-2.46746	1.18055	.101	-5.3084	.3734
O'Neal-Millerville	Fixed Control	ALINEA	-2.45523	3.20083	.725	-10.1578	5.2473
		Mixed	-12.93043*	3.20083	.000	-20.6330	-5.2279
	ALINEA	Fixed Control	2.45523	3.20083	.725	-5.2473	10.1578
		Mixed	-10.47520*	3.20083	.005	-18.1777	-2.7727
	Mixed	Fixed Control	12.93043*	3.20083	.000	5.2279	20.6330
		ALINEA	10.47520*	3.20083	.005	2.7727	18.1777

Vehicles' Hours Traveled (VHT)

Using the simulation results, VHT were calculated as the multiplication of the throughput by the average travel times. The VHT for the different strategies were calculated as average values for each section along the corridor. In addition, the VHT were also aggregated over the entire corridor. The calculations were performed over the ramp meters' period of operation (6:00-9:00 a.m., for the westbound, and 3:00-7:00 p.m., for the eastbound). In the following sections, a discussion for the corridor level VHT and the section-by-section level VHT is presented.

Corridor Level Analysis

The estimated average VHT over the entire corridor are shown in Table 14 for the different ramp metering strategies. For the eastbound direction, the results show that the average VHT for the mixed ramp metering control is less than that for the fixed-time control by around 6.5 veh-hrs. The table also shows that the VHT for the ALINEA is less than that of the fixed-time control by around 2.5 veh-hrs. These results do not show any practical significance in the VHT improvement for the eastbound direction. On the other hand, for the westbound direction, the ALINEA local ramp metering strategy reduced the VHT by approximately 197 veh-hrs when compared to the current fixed-time control. Whereas, for the mixed control the VHT was reduced by around 195 veh-hrs compared to the fixed-time control which is practically has the same effect as ALINEA local control case. The table shows also that the VHT for the eastbound direction are less than those for the westbound direction, which confirms that the eastbound direction is free flowing. This explains the reason for not having significant differences in the VHT for that direction.

Table 14
Average vehicles hours travelled over the corridor

Strategy	VHT (veh-hr)	
	Eastbound	Westbound
Fixed-time	992.3	3199.3
ALINEA	989.9	3002.1
Mixed	985.8	3004.6

Further comparative statistical ANOVA was performed between the different ramp metering strategies using both the sectional VHT and the aggregated corridor VHT. The analysis was performed at 5% level of significance to investigate the statistical significance of the VHT reductions resulting from each strategy. The ANOVA test results for the corridor level are shown in Table 12. The results show that there was no significant change in the VHT between the different strategies for the eastbound direction with a p-vale of 0.478. Whereas, for the westbound direction, the table shows that the VHT were significantly changing between the different strategies with a p-value less than 0.05.

Table 15
Comparative ANOVA test results for the different ramp metering strategies(VHT)

Direction	Level of analysis	Sum of Squares	df	Mean Square	F	P-value
Eastbound	Between Strategies	3200.912	2	1600.456	.748	.478
	Within Strategies	121890.977	57	2138.438		
	Total	125091.889	59			
Westbound	Between Strategies	512069.183	2	256034.592	12.956	.000
	Within Strategies	1126430.723	57	19761.943		
	Total	1638499.907	59			

For the eastbound direction, no further analysis is required because there were no statistically significant differences found in the VHT values. Whereas, for the westbound direction, to determine the strategy with the lowest VHT, Post Hoc tests (Tukey) were performed. The results in Table 16 show no significant change in the VHT values between ALINEA and the mixed ramp metering strategies, while both strategies reduced VHT significantly compared to the fixed-time strategy.

Table 16
Post Hoc Tukey test results for the different ramp metering strategies (VHT)

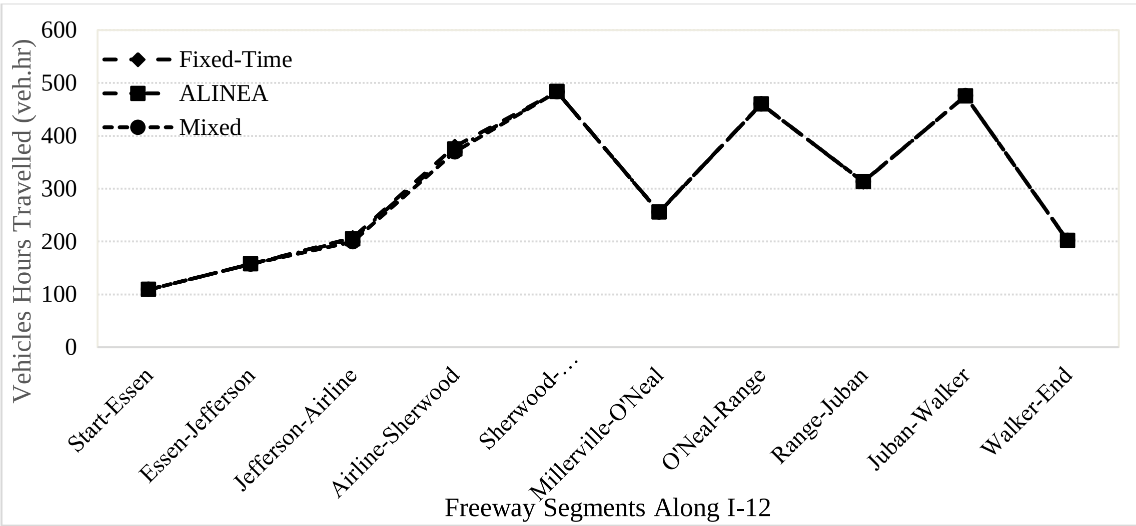
Direction	(I) Strategy	(J) Strategy	Mean Difference (I-J)	Std. Error	P-value	95% Confidence Interval	
						Lower Bound	Upper Bound
Westbound	Fixed Control	ALINEA	197.25*	44.454	.0001	90.27	304.22
		Mixed	194.669*	44.454	.0001	87.69	301.64
	ALINEA	Fixed Control	-197.250*	44.454	.0001	-304.22	-90.27
		Mixed	-2.580	44.454	.998	-109.55	104.39
	Mixed	Fixed Control	-194.669*	44.454	.0001	-301.64	-87.69
		ALINEA	2.580	44.454	.998	-104.39	109.55

* indicates that the difference is statistically significant.

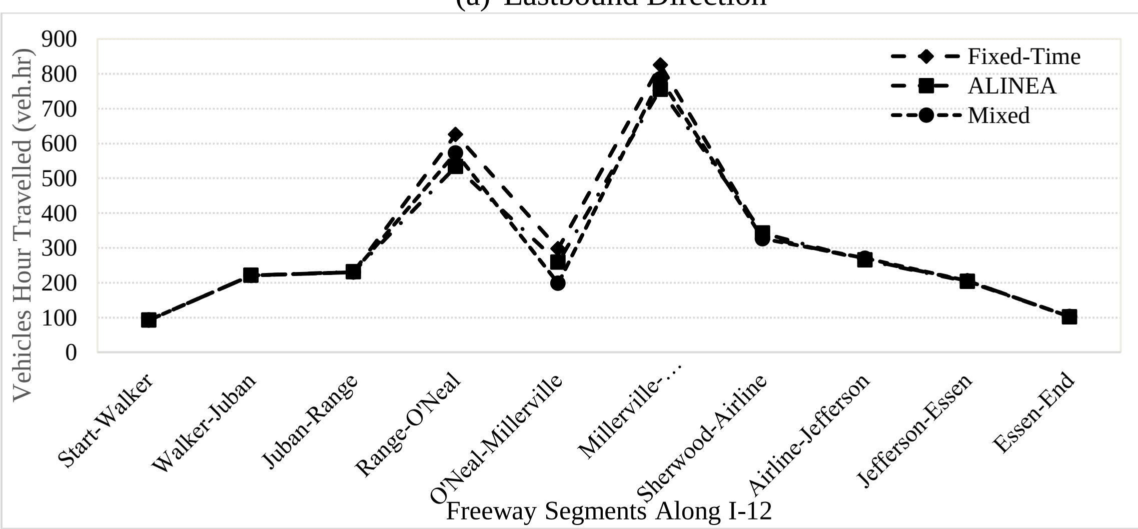
Section Level Vehicles Hours Traveled (VHT)

The section level analysis was performed to show more detailed section-by-section results for the impact of the different strategies, see Appendix B. The section-by-section VHT show the sections that benefited the most from each ramp metering strategy for each direction. The VHT values for each section are shown in Figure 15. The figure shows that, for the eastbound direction, both the mixed and the ALINEA ramp metering strategies did not show any improvement in the VHT values that can be noticed at any of the sections; see

Figure 15-a. On the other hand, for the westbound direction, only three sections showed significant improvement in the VHT values when implementing the mixed and the ALINEA ramp metering strategies. As shown in Figure 15-b, these sections include the ramp meters that control the traffic between Range to O'Neal, O'Neal to Millerville, and Millerville to Sherwood.



(a) Eastbound Direction



(b) Westbound Direction

Figure 15
Section-by-section average VHT results (veh.hr)

The improvements in the VHT values shown in Figure 15-b were further investigated statistically using the Post Hoc pairwise Tukey test. The statistical analysis results are shown in Table 17. The table shows that, for the section between Range and O'Neal, while there was no significant change in the VHT between the mixed and the ALINEA strategies, both of these strategies showed significant improvement in the VHT when compared to the fixed-time control. For the section between O'Neal and Millerville, the mixed control strategy significantly improved the VHT values when compared to the fixed-time and ALINEA control strategies. However, for the section between Millerville and Sherwood, only ALINEA ramp metering strategy showed a significant improvement in the VHT when compared to the fixed-time control strategy.

Table 17
Section-by-section post hoc tukey test results for the different ramp metering strategies

Dependent Variable	(I) Strategy	(J) Strategy	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Range-O'Neal	Fixed Control	ALINEA	92.36147*	18.36670	.000	48.1635	136.5594
		Mixed	53.15462*	18.36670	.015	8.9567	97.3526
	ALINEA	Fixed Control	-92.36147*	18.36670	.000	-136.5594	-48.1635
		Mixed	-39.20685	18.36670	.092	-83.4048	4.9911
	Mixed	Fixed Control	-53.15462*	18.36670	.015	-97.3526	-8.9567
		ALINEA	39.20685	18.36670	.092	-4.9911	83.4048
O'Neal-Millerville	Fixed Control	ALINEA	38.98541	23.96649	.243	-18.6880	96.6588
		Mixed	99.75765*	23.96649	.000	42.0843	157.4310
	ALINEA	Fixed Control	-38.98541	23.96649	.243	-96.6588	18.6880
		Mixed	60.77224*	23.96649	.037	3.0989	118.4456
	Mixed	Fixed Control	-99.75765*	23.96649	.000	-157.4310	-42.0843
		ALINEA	-60.77224*	23.96649	.037	-118.4456	-3.0989
Millerville-Sherwood	Fixed Control	ALINEA	69.59992*	25.19885	.021	8.9610	130.2389
		Mixed	39.65881	25.19885	.265	-20.9801	100.2978
	ALINEA	Fixed Control	-69.59992*	25.19885	.021	-130.2389	-8.9610
		Mixed	-29.94111	25.19885	.465	-90.5801	30.6978
	Mixed	Fixed Control	-39.65881	25.19885	.265	-100.2978	20.9801
		ALINEA	29.94111	25.19885	.465	-30.6978	90.5801

Optimal Ramp Metering Strategy

The results showed that none of the adaptive ramp metering strategies affected the traffic conditions on the eastbound direction. The current traffic conditions on this direction are free flowing with the fixed-time strategy; hence, no further improvements could be achieved. For the westbound direction, both the ALINEA and the mixed strategy cases showed significant improvements in the traffic conditions compared to the fixed-time control. More specifically, three main locations benefited the most from both strategies. When the performance of the two strategies was compared, the mixed control was superior to ALINEA local control.

In summary, the analysis results showed the current demand on the eastbound direction can be controlled by the fixed-time control. Whereas, for the westbound direction, the mixed strategies (HERO coordinated strategy at the locations in Figure 3 and ALINEA local strategy at the other locations) is recommended to be implemented.

Cost Estimate of the Optimal Strategy

Based on the previous discussion, the mixed strategy was recommended to be implemented on the westbound direction on I-12. Whereas, for the eastbound, the fixed-control was recommended to remain in operation. Therefore, in order to implement this strategy, a rough cost estimate was prepared. This estimate includes the prices of the detectors and the control units. Implementing the optimal strategy requires detectors to be placed on the downstream of each on-ramp (to detect the downstream traffic conditions), detectors to be placed on the ramps (to detect the ramp queues, to measure the traffic arrivals and departures, and to detect the vehicle presence at the on-ramp entrance to I-12), and control units (to control the signal timing based on the traffic conditions measured by the aforementioned detectors).

The required number of detectors for all the ramps' locations are 56. The unit price of each detector according to the Office of the Assistant Secretary for Research and Technology (OST-R) is around $500. As a result, the total detectors' cost adds up to around $28,000. For the control units, each ramp location requires one unit which adds up to 8 units for the 8 metered ramps. The unit price for each control unit according to the OST-R is $20,000. This makes the total cost for the control units around $160,000. As such, the total equipment price to implement the recommended strategy on the westbound direction is around $188,000. This is a rough estimation that is subject to change according to the market prices.

CONCLUSIONS

This simulation-based evaluation study examined the effectiveness of different ramp metering strategies to improve the traffic conditions on I-12. The evaluation included a comparative speed analysis, travel time savings, and vehicles hours traveled (VHT) savings. The main objective was to identify the optimal ramp metering strategy that achieves more significant improvements in traffic conditions on the I-12 corridor. The tested strategies included the fixed-time ramp metering control, the ALINEA local ramp metering control, and the mixed strategy ramp metering control (which included a combination of HERO coordinated strategy and ALINEA local strategy). Queue override strategy was also used to flush the on-ramp queues in case they exceed certain limits. The base case in this study included the fixed-time ramp metering control with queue override strategy. The comparative analysis was performed between each of the ALINEA and mixed strategies and the base case. In the mixed strategy, the coordination was performed between two on-ramps on the eastbound and between two sets of two on-ramps on the westbound. For each strategy, the analysis was performed for the aggregated measures on the entire corridor as well as for each section of the corridor (a section is defined by a ramp meter location).

For the eastbound direction, the travel time for a vehicle traveling along the entire corridor was reduced by 6 seconds when the mixed strategy was tested and by 2 seconds when the ALINEA strategy was tested. These travel time savings are not practically significant for a vehicle traveling along the 15 mile corridor. Similarly, the travel speed along the entire corridor was improved by 0.2 mph for the ALINEA strategy and 0.4 mph for the mixed strategy. These results affected the VHT values for both strategies. The VHT was reduced by 2.5 veh-hrs for the ALINEA strategy and by 6.5 veh-hrs for the mixed strategy. These results showed that none of the adaptive control strategies were able to improve the traffic conditions in the eastbound direction. This was investigated further using the statistical ANOVA analysis which showed no significant change in any of the used measures (speed, travel time, and VHT). These results were expected since the eastbound direction is operating with the fixed-time control at free flow conditions. This means that no further improvements can be expected or achieved for the operational characteristics of the corridor.

For the westbound direction, more significant results were obtained for all the measures. For ALINEA strategy, the average travel time along the corridor was reduced by around 20 seconds, the average speed was increased by around 1 mph, and the VHT were reduced by around 197 veh-hrs compared to the fixed-time control strategy. For the mixed strategy, the average travel time along the corridor was reduced by around 40 seconds, the average speed was increased by around 2 mph, and the VHT were reduced by around 195 veh-hrs compared to the fixed-time control strategy. These improvements achieved by the ALINEA and the mixed strategy in the performance of the westbound direction are practically more significant than those achieved in the eastbound direction. The statistical comparative ANOVA analysis was performed to measure the statistical significance of these improvements. The analysis results showed that both the ALINEA and the mixed strategies significantly improved the overall operating conditions along the corridor when compared to the base case. For the corridor level analysis, Post Hoc Tukey tests showed significant reduction in VHT values achieved by both ALINEA and mixed strategies; whereas, speed and the travel time values improved significantly for only the mixed strategy.

Further analysis was performed for the westbound corridor to identify the ramp meters' locations that benefited the most from each strategy. The section-by-section calculated measures were used. The results showed that most of the sections (ramp meters' location) did not show any improvements in any of the measures. Only three sections showed significant improvements in terms of the travel time and VHT (Range-O'Neal, O'Neal-Millerville, and Millerville-Sherwood), and two sections showed significant improvement in terms of the travel speed (Range-O'Neal and O'Neal-Millerville). For the section from Range to O'Neal, the travel time was reduced by around 43 seconds for ALINEA strategy; whereas, the reduction in the travel time was around 26 seconds for the mixed strategy. Similarly, the average speed for this section was increased by around 6.1 mph, for ALINEA strategy, and increased by around 3.6 mph, for the mixed strategy. As a result, the VHT on this section was reduced by around 92 veh.hrs, for ALINEA strategy, and reduced by around 53 veh.hrs, for the mixed strategy. For the section from O'Neal to Millerville, the results showed more significant improvement for the mixed strategy when compared to the ALINEA local strategy. The reduction in the travel time was around 34 seconds for the mixed and 11 seconds for the ALINEA strategy. The speed results showed that while the ALINEA strategy was able to increase the speed at O'Neal-Millerville section by around 2.5 mph, the mixed strategy increased the speed by around 12.9 mph for the same section. Similarly, the mixed strategy achieved more significant reductions in the VHT compared to the ALINEA. The VHT reduction for the latter strategy was around 39 veh.hrs; whereas, the former strategy achieved a VHT reduction by around 100 veh.hrs. For the section between Millerville and Sherwood, there was no improvement in the speed when using any of the adaptive control strategies. However, the travel time was reduced by around 16 seconds for ALINEA, and 10 seconds for the mixed strategy. More so, the VHT was reduced by around 70 veh.hrs for ALINEA, and 40 veh.hrs for the mixed strategy.

The speed profiles for the current traffic conditions in the westbound direction showed that the speed values over the aforementioned three sections were the lowest along the corridor. This means that there are bottlenecks at those specific sections. Using any of the adaptive strategies (ALINEA or mixed) was able to improve the traffic conditions at these sections. When the improvements achieved by the two strategies were compared to each other, the mixed strategy showed superiority to the ALINEA strategy on two sections, while the ALINEA was more superior on only one section.

The evaluation results show that none of the strategies achieved any significant improvements in the traffic conditions for the eastbound direction. However, for the westbound direction, the travel time, speed, and VHT improved significantly along the corridor. The section-by-section analysis for the westbound direction showed that while most of the sections did not experience any improvements, the traffic conditions on three sections were improved significantly. The results also showed that while the ALINEA strategy achieved more significant improvements at one section, the mixed strategy achieved more significant improvements at two sections. More so, the improvements achieved by the mixed strategy for the two sections were more significant than those achieved by ALINEA for the other section. Therefore, the mixed ramp metering strategy can be selected as the optimal strategy to operate the on-ramps of the westbound I-12 corridor.

Overall, the results showed statistically significant improvements for the westbound direction. This was achieved for any of the adaptive control strategies (ALINEA and Mixed). While the improvements on some sections are significant statistically and practically, the overall improvements on the entire westbound direction were not practically significant. When investigating the collected video recordings for the westbound direction, they showed that one of the main reasons for the bottlenecks is the off-ramps spilling back on I-12. These spillbacks are resulting from the high off-ramps traffic volumes that are not accommodated by the traffic signals on the surface streets at the end of the off-ramps. This problem could be minimized if these traffic signals were coordinated with the ramp meters on I-12. This could help reduce the demand on the traffic signals on the surface streets and also allow longer green times for the off-ramp traffic at the surface streets' ends.

RECOMMENDATIONS

The following recommendations are made based on the findings of this study:

1. Further investigation should consider coordination between the ramp meters and the traffic signals on the surface streets may help alleviate the spillbacks from the off-ramps on the interstate.
2. Further research may consider application of mixed control strategies at the same ramp locations according to the traffic condition and the time of operation. In other words, an on-ramp can be controlled by the fixed-time control for specific traffic conditions, but when these conditions change, according to the time of the day, an adaptive control can be activated.

ACRONYMS, ABBREVIATIONS & SYMBOLS

ALINEA	Asservissement Linéaire d'Entrée Auotroutière
ANN	Artificial Neural Network
ANOVA	Analysis of Variance
ARMS	Advanced Real-time Metering System
ATM	Active Traffic Management
BEEX	Balanced Efficiency and Equity
CPM	Crash Prediction Model
DC	Demand Capacity
DOTD	Louisiana Department of Transportation and Development
FRESIM	FREeway SIMulation
GPS	Global Positioning System
HERO	Heuristic Ramp Metering
IRIS	Intelligent Road Information System
LTRC	Louisiana Transportation Research Center
MANOVA	Multivariate Analysis of Variance
MCW	Monsh-Citylin-West Gate
OCC	Occupancy
SZM	Stratified Zone Ramp Metering
VAP	Vehicle Actuated Programming
VHT	Vehicle hours travelled
VSL	Variable Speed Limit
WSDOT	Washington State Department of Transportation

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APPENDIX A

VAP Codes for the Different Ramp Metering Strategies

This appendix shows detailed codes written in the Vehicle Actuated Programming (VAP) interface in VISSIM simulation software.

1. Fixed-Time Ramp Metering and ALINEA

```
PROGRAM DRUSILLAEB; /* FIXED timing vs Basic ALINEA Strategy */

VAP_FREQUENCY 1;

CONST
        Algorithm=2,     /*Algorithm=1 if fixed timing , 2 if ALINEA, 3 if ALINEA with queue override tactic*/
        QueueOverRide=1,          /*1 if queueoverride and 0 if no queueoverride*/

        QueueCountInterval = 20,  /*update timing every 20 seconds*/
        OccupancyInterval = 20,
        GreenInterval = 2,                    /*Green time is 2 seconds to allow one vehicle at a time to enter the
mainline*/

        MaxRate = 1800,                       /*maximum ramp flow rate*/
        MinRate = 400,            /*minimum ramp flow rate*/
        FixedRate = 900,                      /*fixed ramp flow rate, only rates at: 400, 450, 515, 600, 720, 900, 1200*/
        NumberMeterLane = 1,      /*Number of metered lanes*/


        PresenceDetector_1 = 49,  /*Presence detectors on ramps based on which a vehicle calling to enter the mainline
is detected*/
        QueueDetector_Advance = 50,         /*For queue detection at the end of the on-ramp*/
        Queue_Threshold = 0.1,    /* For ramp queue detection */

        /*Data Collection Parameters*/
        StartTime=3600,
        EndTime=18000, /* 9000 for AM peak and 14400 for PM peak*/

      MAX_LANE = 4,               /*number of lanes on the mainline*/
      KR = 70,                    /*ALINEA constant*/
      OCC_OPT = 0.29;             /*Optimum or critical occupancy*/

/*************************************************************************************/
/***********************************ARRAYS******************************************/
/*************************************************************************************/

ARRAY
      detNo[ 4, 1 ] = [[24], [25], [26], [27]]; /*detectors array on the mainline*/
/************************************************************************************/
/********************************SUBROUTINES***************************************/
/*************************************************************************************/

/********************Fixed Time Metering *********************************************/
/***********************************************************************************/
         SUBROUTINE FIXED;
```

```
        IF Occupancy (PresenceDetector_1) > 0 THEN
            sg_red (1);         /*If no vehicle waiting on the ramp switch the signal to red*/
        ELSE
            MeterPrevious :=FixedRate;
            MeterRate :=MeterPrevious;
            RedInt := (3600/MeterRate)*NumberMeterLane - GreenInterval;
        END;

        IF t_green (1) >=GreenInterval THEN
            sg_red (1);
        END;

        IF (t_red (1) >= RedInt) THEN         /* Red has reached the maximum so we need to check if there
are vehicles waiting to enter or not */
            IF Occupancy (PresenceDetector_1) > 0 THEN
                sg_green (1);
                START (greenTimer1);
            END;
        END;

        IF greenTimer1 >= GreenInterval THEN
            sg_red (1);
        END;

        RESET (greenTimer1);
        STOP (greenTimer1).
/*********************************************************************************/
/***************************Fixed Time Metering Works with Queue Override*************/
/**********************************************************************************/
    SUBROUTINE FIXED2;
        IF Occupancy (PresenceDetector_1) > 0 THEN
            sg_red (1);         /*If no vehicle waiting on the ramp switch the signal to red*/
        ELSE
            MeterPrevious :=FixedRate;
            MeterRate :=MeterPrevious;
            RedInt := (3600/MeterRate)*NumberMeterLane - GreenInterval;
        END.
/**********************************************************************************/
/**************************************ALINEA Strategy*****************************/
/*********************************************************************************/
    SUBROUTINE ALINEA;

        IF CountTimer = OccupancyInterval THEN
            TRACE (variable (MeterPrevious));
            IF OccupancyInterval = 1 THEN       /* set interval to 1 second for reporting */
S00Z001:            laneNo := 1;
S00Z002:            IF laneNo <= MAX_LANE THEN
S01Z002:                IF detNo[ laneNo, 1 ] > 0 THEN
S02Z002:                Occup:= Occup+ Occup_rate( detNo[ laneNo, 1 ]);
S02Z003:                laneNo := laneNo + 1;
                        GOTO S00Z002
                        END;
            END;
                AverageOcc := Occup/MAX_LANE;
                AvgOccup_DownStreamDet := AverageOcc;
            ELSE
                AvgOccup_DownStreamDet := Occup_DetDownStream / (OccupancyInterval);
            END;
```

```
                    MeterRate := MeterPrevious + KR*(OCC_OPT-AvgOccup_DownStreamDet)*100;
                    /*Metering Rate According to ALINEA equation.... If the occupancy downstream is larger
than the optimum, the meterrate will be less than the metering rate in the previous time step*/
                    IF MeterRate >= MaxRate THEN
                        MeterRate := MaxRate;
                        RedInt := (3600/MeterRate)*NumberMeterLane - GreenInterval;
                        MeterPrevious := MeterRate;
                    ElSE
                        IF MeterRate <= MinRate THEN
                            MeterRate := MinRate;
                            RedInt := (3600/MeterRate)*NumberMeterLane - GreenInterval;
                            MeterPrevious := MeterRate;
                        ELSE
                            RedInt := (3600/MeterRate)*NumberMeterLane - GreenInterval;
                            MeterPrevious := MeterRate;
                        END;
                    END;
                    /*******FlowRate on the mainline**********/
S00Z034:            laneNo := 1;
S00Z035:            IF laneNo <= MAX_LANE THEN
S01Z035:                IF detNo[ laneNo, 1 ] > 0 THEN
S02Z035:                SumVeh := SumVeh+ rear_ends( detNo[ laneNo, 1 ]);
S02Z036:                laneNo := laneNo + 1;
                        GOTO S00Z035
                        END;
                END;
                    FlowRate := (SumVeh/OccupancyInterval)*3600;        /*the counted rear-ends are
converted into hourly flow rate*/

                    TRACE (variable (AvgOccup_DownStreamDet, FlowRate));        /*record these data in
the output*/
                    TRACE (variable (MeterRate, RedInt));

                    RESET (CountTimer);
                    Occup_DetDownStream :=0;
S00Z047:            laneNo := 1;
S00Z048:            IF laneNo <= MAX_LANE THEN
S01Z048:                IF detNo[ laneNo, 1 ] > 0 THEN
S02Z048:                clear_rear_ends( detNo[ laneNo, 1 ]);
S02Z049:                laneNo := laneNo + 1;
                        GOTO S00Z048
                        END;
                END;

                ELSE
S00Z055:            laneNo := 1;
S00Z056:            IF laneNo <= MAX_LANE THEN
S01Z056:                IF detNo[ laneNo, 1 ] > 0 THEN
S02Z056:                Occup:= Occup+ Occup_rate( detNo[ laneNo, 1 ]);
S02Z057:                laneNo := laneNo + 1;
                        GOTO S00Z002
                        END;
                END;
                    AverageOcc := Occup/MAX_LANE;
                    AvgOccup_DownStreamDet := AverageOcc;
                END.
/**************************************************************************************/
/********************Queue Override Tactic and Meter Operation***********************/
/**********************************************************************************/
```

```
	SUBROUTINE MeterOperation;
	/*Single-lane meter */

	IF t_green (1) >=GreenInterval THEN
		IF (QueueOverRide AND QueueSpill) THEN
			sg_green (1); /******************************************/
			MeterPrevious :=MaxRate;    /*Do not start red and keep the ramp on green to flush*/
			IF (SimuTime >= StartTime) AND (SimuTime < EndTime) THEN
				MeterFlushTime := MeterFlushTime+1;
				TRACE (variable (SimuTime, MeterFlushTime));
			END;
		ELSE
			sg_red (1);		/*If no queue on the ramp then switch the signal to red*/
		END;
	END;

	IF (t_red (1) >= RedInt) THEN		/* Red has reached the maximum so we need to check if there are vehicles
waiting to enter or not */
		IF Occupancy (PresenceDetector_1) > 0 THEN
			sg_green (1);
			START (greenTimer1);
		END;
	END;

	IF greenTimer1 >= GreenInterval THEN
		IF (QueueOverRide AND QueueSpill) THEN
			MeterPrevious :=MaxRate;    /*Do not start red and keep the ramp on green to flush*/
			sg_green (1); /*************************************/
		ELSE
			sg_red (1);		/*If no queue on the ramp then switch the signal to red*/
		END;
	END;

	RESET (greenTimer1);
	STOP (greenTimer1).
/*************************************************************************************/
/********************************This is the main Program******************************/
/************************************************************************************/
	TRACE (all);
	START (QueueTimer);
	START (CountTimer);
	SimuTime := SimuTime + 1;

	IF QueueTimer = (QueueCountInterval + 1) THEN
		AvgOccup_AdvanceQueueDet := Occup_AdvanceQueueDet / QueueCountInterval;
		QueueSpill := AvgOccup_AdvanceQueueDet >=Queue_Threshold;
		RESET (QueueTimer);
		Occup_AdvanceQueueDet := 0;
	ELSE
		Occup_AdvanceQueueDet := Occup_AdvanceQueueDet + Occup_rate (QueueDetector_Advance);
	END;

	IF Algorithm = 1 THEN
		GOSUB FIXED;
	ELSE
		IF Algorithm = 2 THEN
			GOSUB FIXED2;
			GOSUB MeterOperation;
		ELSE
			IF Algorithm = 3 THEN
```

```
                                        GOSUB ALINEA;
                                        GOSUB MeterOperation;
                              END;
                    END;
          END.
/*************************************************************************************/
```

2. LINKED and ALINEA Ramp Metering

```
PROGRAM DRUSILLAEB; /* ALINEA - LINKED Strategy */

VAP_FREQUENCY 1;

CONST
          QueueOverRide=1,            /*1 if queueoverride and 0 if no queueoverride*/
           Queue_Threshold = 0.1,      /* For ramp queue detection */
           Max_Threshold= 0.3, /*activation threshold for linked control.3*/
           Min_Threshold= 0.15, /*deactivation threshold.15*/
            StartTime= 3600,
            EndTime= 18000, /* 9000 for AM peak and 14400 for PM peak*/
            QueueCountInterval = 20,  /*update timing every 20 seconds*/
            OccupancyInterval = 20,
            GreenInterval = 2,                    /*Green time is 2 seconds to allow one vehicle at a time to enter the
mainline*/
            MaxRate = 1800,                       /*maximum ramp flow rate*/
            MinRate = 400,             /*minimum ramp flow rate*/
            NumberMeterLane_1 = 1,  /*Number of metered lanes- Location 1*/
            NumberMeterLane_2 = 1,  /*Number of metered lanes- Location 2*/
                   MAX_LANE_1 = 4,                       /*number of lanes on the mainline-1to3*/
                   MAX_LANE_2 = 7,                       /*number of lanes on the mainline-4to6*/
            PresenceDetector_1 = 118, /*Presence detectors on ramps based on which a vehicle calling to enter the mainline
is detected*/
            PresenceDetector_2 = 113,
                   QueueDetector_Advance_1 = 119,
                   QueueDetector_Advance_2 = 114,
                   QueueDetector_Departure_1 = 165,
                   QueueDetector_Departure_2 = 167,
                   ArrivalDetector_1 = 166,
                   ArrivalDetector_2 = 168,
                   KR = 70,                    /*ALINEA constant*/
                   OCC_OPT = 0.29,             /*Optimum or critical occupancy*/
                   Desired_Density= 0.29, /*(veh/mile/lane) at merging area or downstream bottleneck, shall be
optimize.29*/
                   W_max_o_1= 40 ,/*maximum admissible number of vehicles in the queue of on-ramp 1000ft(lenght of
ramp)/24ft(per eahc vehicle)*/
                   W_max_o_2= 20 ;/*maximum admissible number of vehicles in the queue of the on-ramp 500ft (lenght
of ramp)/24ft (per eahc vehicle)*/

/*********************************ARRAYS*****************************************/
/*************************************************************************************/
ARRAY
       detNo[ 7, 1 ] = [ [34], [35], [36], [120], [115], [116], [117]]; /*detectors array on the mainline*/
/*************************************************************************************/
/******************************SUBROUTINES**************************************/
/*************************************************************************************/
/****************************Queue Override Meter Operation*************************/
/*********************************************************************************/
          SUBROUTINE QOverride1;

          IF t_green (1) >=GreenInterval THEN
```

```
            IF (QueueOverRide AND QueueSpill_1) THEN
                sg_green (1); /*******************************************/
                MeterPrevious_1 :=MaxRate;          /*Do not start red and keep the ramp on green to
flush*/
                IF (SimuTime >= StartTime) AND (SimuTime < EndTime) THEN
                    MeterFlushTime_1 := MeterFlushTime_1+1;
                    TRACE (variable (SimuTime, MeterFlushTime_1));
                END;
            ELSE
                sg_red (1);         /*If no queue on the ramp then switch the signal to red*/
            END;
        END;

        IF (t_red (1) >= RedInt_1) THEN  /* Red has reached the maximum so we need to check if there are vehicles
waiting to enter or not */
            IF Occupancy(PresenceDetector_1) > 0 THEN
                sg_green (1);
                START (greenTimer1);
            END;
        END;

        IF greenTimer1 >= GreenInterval THEN
            IF (QueueOverRide AND QueueSpill_1) THEN
                MeterPrevious_1 :=MaxRate;          /*Do not start red and keep the ramp on green to
flush*/
                sg_green (1);
            ELSE
                sg_red (1);         /*If no queue on the ramp then switch the signal to red*/
            END;
        END;

        RESET (greenTimer1);
        STOP (greenTimer1).
/*********************************************************************************/
/********************************Meter Operation*************************************/
/*********************************************************************************/
        SUBROUTINE MeterOperation1;

        IF t_green (1) >=GreenInterval THEN
            sg_red (1);         /*If no queue on the ramp then switch the signal to red*/
        END;
        IF (t_red (1) >= RedInt_1) THEN         /* Red has reached the maximum so we need to check if there are vehicles
waiting to enter or not */
            IF Occupancy (PresenceDetector_1) > 0 THEN
                sg_green (1);
                START (greenTimer1);
            END;
        END;
        IF greenTimer1 >= GreenInterval THEN
            sg_red (1);         /*If no queue on the ramp then switch the signal to red*/
        END;

        RESET (greenTimer1);
        STOP (greenTimer1).
/**********************************************************************************/
/********************************RAMP TWO*******************************************/
/**********************************************************************************/
/**********************************************************************************/
/***************************Queue Override Meter Operation*************************/
/*********************************************************************************/
```

```
SUBROUTINE QOverride2;

IF t_green(2) >=GreenInterval THEN
		IF (QueueOverRide AND QueueSpill_2) THEN
				sg_green(2); /********************/
				MeterPrevious_2 := MaxRate;		/*Do not start red and keep the ramp on green to
flush*/
				IF (SimuTime >= StartTime) AND (SimuTime < EndTime) THEN
						MeterFlushTime_2 := MeterFlushTime_2+1;
						TRACE (variable (SimuTime, MeterFlushTime_2));
				END;
		ELSE
				sg_red(2);		/*If no queue on the ramp then switch the signal to red*/
		END;
END;

IF (t_red(2) >= RedInt_2) THEN		/* Red has reached the maximum so we need to check if there are vehicles
waiting to enter or not */
		IF Occupancy (PresenceDetector_2) > 0 THEN
				sg_green(2);
				START(greenTimer2);
		END;
END;

IF greenTimer2 >= GreenInterval THEN
		IF (QueueOverRide AND QueueSpill_2) THEN
				MeterPrevious_2 :=MaxRate;		/*Do not start red and keep the ramp on green to
flush*/
				sg_green(2); /*********************/
		ELSE
				sg_red(2);		/*If no queue on the ramp then switch the signal to red*/
		END;
END;

RESET (greenTimer2);
STOP (greenTimer2).
/*******************************************************************************/
/*****************************Meter Operation**********************************/
/*******************************************************************************/
SUBROUTINE MeterOperation2;

IF MeterRate_2 >0 THEN
		IF t_green (2) >=GreenInterval THEN
				sg_red (2);		/*If no queue on the ramp then switch the signal to red*/
		END;
		IF (t_red (2) >= RedInt_2) THEN		/* Red has reached the maximum so we need to check if there
are vehicles waiting to enter or not */
				IF Occupancy (PresenceDetector_2) > 0 THEN
						sg_green (2);
						START (greenTimer2);
				END;
		END;
		IF greenTimer2 >= GreenInterval THEN
				sg_red (2);		/*If no queue on the ramp then switch the signal to red*/
		END;
ELSE
		sg_red(2);
END;
```

```
        RESET (greenTimer2);
        STOP (greenTimer2).
/*************************************************************************************/
/*************************************LINKED**************************************/
/**************************************************************************************/
        SUBROUTINE LINKED;

                IF CountTimer = OccupancyInterval THEN
S00e001:                        laneNo_2 := 4;
S00e002:                IF laneNo_2 <= MAX_LANE_2 THEN
S01e002:                                IF detNo[ laneNo_2, 1 ] > 0 THEN
S02e002:                                Occup_2:= Occup_2+ Occup_rate( detNo[ laneNo_2, 1 ]);
S02e003:                                laneNo_2 := laneNo_2 + 1;
                                        GOTO S00e002
                                        END;
                END;
                                        Occupancy_2 := Occup_2;
                        AverageOcc_2 := Occupancy_2/(MAX_LANE_2 - MAX_LANE_1);
                        AvgOccup_DownStreamDet_2 := AverageOcc_2;
                        Occup_2 := 0;

                        OptimumFlowControlramp_2 := MeterPrevious_2 + KR*(OCC_OPT-
AvgOccup_DownStreamDet_2)*100;
                        /*Metering Rate According to ALINEA equation.If the occupancy downstream is larger than
the optimum, the meterrate will be less than the metering rate in the previous time step*/

                        OptimumQueueControlramp_2 := (((-1/QueueCountInterval)*(W_max_o_2-
Queue_Length_2))+RampDemandPrevious_2)*3600 ; /*arriving ramp demand*/
                        W_min_o2 :=
(((Queue_Length_1+Queue_Length_2)*(W_max_o_2))/(W_max_o_1+W_max_o_2));
                        LocalControlMeterRate_2 := (((-1/QueueCountInterval)*(W_min_o2-
Queue_Length_2))+RampDemandPrevious_2)*3600;

                        IF (OptimumFlowControlramp_2 < LocalControlMeterRate_2) THEN
                                min_rate_2 := OptimumFlowControlramp_2;
                        ELSE
                                min_rate_2 := LocalControlMeterRate_2;
                        END;
                        IF min_rate_2 > OptimumQueueControlramp_2 THEN
                                CoordinationMeterRate_2 := min_rate_2;
                        ELSE
                                CoordinationMeterRate_2 := OptimumQueueControlramp_2;
                        END;
                        MeterRate_2 := CoordinationMeterRate_2;
                        RedInt_2 := (3600/MeterRate_2)*NumberMeterLane_2 - GreenInterval;
                        MeterPrevious_2 := MeterRate_2;

                        /*******Queue on Ramp2**********/
                        Arrival_2 :=  rear_ends(ArrivalDetector_2) ;
                        Departure_2 :=  rear_ends(QueueDetector_Departure_2) ;
                        Queue_Length_2 := (Arrival_2-Departure_2) + Queue_Length_Previous_2;

                        IF (Queue_Length_2 > 0) THEN
                                Queue_Length_2 := Queue_Length_2;
                        ELSE
                                Queue_Length_2 := 0;
                        END;
                        Queue_Length_Previous_2 := Queue_Length_2;
                        RampDemand_CurrentInterval_2 := (Arrival_2)/OccupancyInterval ;
                        RampDemandPrevious_2 := RampDemand_CurrentInterval_2;
```

```
S001001:                laneNo_1 := 1;
S001002:                IF laneNo_1 <= MAX_LANE_1 THEN
S011002:                        IF detNo[ laneNo_1, 1 ] > 0 THEN
S021002:                        Occup_1:= Occup_1+ Occup_rate( detNo[ laneNo_1, 1 ]);
S021003:                        laneNo_1 := laneNo_1 + 1;
                                GOTO S001002
                                END;
                        END;
                                        Occupancy_1 := Occup_1;
                        AverageOcc_1 := Occupancy_1/MAX_LANE_1;
                        AvgOccup_DownStreamDet_1 := AverageOcc_1;
                        Occup_1 := 0;

                        OptimumFlowControlramp_1 := MeterPrevious_1 + KR*(OCC_OPT-
AvgOccup_DownStreamDet_1)*100;
                        OptimumQueueControlramp_1 := ((-1/QueueCountInterval)*(W_max_o_1 -
Queue_Length_1)+RampDemandPrevious_1) ; /*arriving ramp demand*/

                        IF (OptimumFlowControlramp_1>= OptimumQueueControlramp_1) THEN
                                MeterRate_1 := OptimumFlowControlramp_1;
                        ELSE
                                MeterRate_1 := OptimumQueueControlramp_1;
                        END;

                        IF MeterRate_1 >= MaxRate THEN
                                MeterRate_1 := MaxRate;
                                RedInt_1 := (3600/MeterRate_1)*NumberMeterLane_1 - GreenInterval;
                                MeterPrevious_1 := MeterRate_1;
                        ElSE
                                IF MeterRate_1 <= MinRate THEN
                                        MeterRate_1 := MinRate;
                                        RedInt_1 := (3600/MeterRate_1)*NumberMeterLane_1 - GreenInterval;
                                        MeterPrevious_1 := MeterRate_1;
                                ELSE
                                        RedInt_1 := (3600/MeterRate_1)*NumberMeterLane_1 - GreenInterval;
                                        MeterPrevious_1 := MeterRate_1;
                                END;
                        END;

                        /*******Queue on Ramp1**********/
                        Arrival_1 :=  rear_ends(ArrivalDetector_1);
                        Departure_1 :=  rear_ends(QueueDetector_Departure_1);
                        Queue_Length_1 := (Arrival_1-Departure_1) + Queue_Length_Previous_1;

                        IF (Queue_Length_1 > 0) THEN
                                Queue_Length_1 := Queue_Length_1;
                        ELSE
                                Queue_Length_1 := 0;
                        END;
                        Queue_Length_Previous_1 := Queue_Length_1;
                        RampDemand_CurrentInterval_1 := (Arrival_1)/OccupancyInterval ;
                        RampDemandPrevious_1 := RampDemand_CurrentInterval_1;

                        RESET (CountTimer);
S00l047:                laneNo_2 := 4;
S00l048:                IF laneNo_2 <= MAX_LANE_2 THEN
S01l048:                        IF detNo[ laneNo_2, 1 ] > 0 THEN
S02l048:                        clear_rear_ends( detNo[ laneNo_2, 1 ]);
S02l049:                        laneNo_2 := laneNo_2 + 1;
```

```
                        GOTO S00l048
                                END;
                END;
                        clear_rear_ends(ArrivalDetector_2);
                        clear_rear_ends(QueueDetector_Departure_2);

S001047:                laneNo_1 := 1;
S001048:                IF laneNo_1 <= MAX_LANE_1 THEN
S011048:                        IF detNo[ laneNo_1, 1 ] > 0 THEN
S021048:                        clear_rear_ends( detNo[ laneNo_1, 1 ]);
S021049:                        laneNo_1 := laneNo_1 + 1;
                                GOTO S001048
                                END;
                END;
                        clear_rear_ends(ArrivalDetector_1);
                        clear_rear_ends(QueueDetector_Departure_1);

                ELSE
S00o055:                laneNo_2 := 4;
S00o056:                IF laneNo_2 <= MAX_LANE_2 THEN
S01o056:                        IF detNo[ laneNo_2, 1 ] > 0 THEN
S02o056:                        Occup_2:= Occup_2+ Occup_rate( detNo[ laneNo_2, 1 ]);
S02o057:                        laneNo_2 := laneNo_2 + 1;
                                GOTO S00o056
                                END;
                END;
                        Occupancy_2 := Occup_2;
                        AverageOcc_2 := Occupancy_2/(MAX_LANE_2 - MAX_LANE_1);
                        AvgOccup_DownStreamDet_2 := AverageOcc_2;
                        Occup_2 := 0;

                        Arrival_2 :=  rear_ends(ArrivalDetector_2);
                        Departure_2 :=  rear_ends(QueueDetector_Departure_2);
                        Queue_Length_2 := (Arrival_2-Departure_2) + Queue_Length_Previous_2;

                        IF (Queue_Length_2 > 0) THEN
                                Queue_Length_2 := Queue_Length_2;
                        ELSE
                                Queue_Length_2 := 0;
                        END;

S001055:                laneNo_1 := 1;
S001056:                IF laneNo_1 <= MAX_LANE_1 THEN
S011056:                        IF detNo[ laneNo_1, 1 ] > 0 THEN
S021056:                        Occup_1:= Occup_1+ Occup_rate( detNo[ laneNo_1, 1 ]);
S021057:                        laneNo_1 := laneNo_1 + 1;
                                GOTO S001056
                                END;
                END;
                        Occupancy_1 := Occup_1;
                        AverageOcc_1 := Occupancy_1/MAX_LANE_1;
                        AvgOccup_DownStreamDet_1 := AverageOcc_1;
                        Occup_1 := 0;

                        Arrival_1 :=  rear_ends(ArrivalDetector_1);
                        Departure_1 :=  rear_ends(QueueDetector_Departure_1);
                        Queue_Length_1 := (Arrival_1-Departure_1) + Queue_Length_Previous_1;
                        IF (Queue_Length_1 > 0) THEN
                                Queue_Length_1 := Queue_Length_1;
                        ELSE
```

```
                        Queue_Length_1 := 0;
                END;

        END.
/*************************************************************************************/
/***************************ALINEA Strategy***************************************/
/*************************************************************************************/
    SUBROUTINE ALINEA;

        IF CountTimer = OccupancyInterval THEN

S00k001:                laneNo_1 := 1;
S00k002:                IF laneNo_1 <= MAX_LANE_1 THEN
S01k002:                        IF detNo[ laneNo_1, 1 ] > 0 THEN
S02k002:                        Occup_1:= Occup_1+ Occup_rate( detNo[ laneNo_1, 1 ]);
S02k003:                        laneNo_1 := laneNo_1 + 1;
                                GOTO S00k002
                                END;
                END;
                                        Occupancy_1 := Occup_1;
                AverageOcc_1 := Occupancy_1/MAX_LANE_1;
                AvgOccup_DownStreamDet_1 := AverageOcc_1;

S00q001:                laneNo_2 := 4;
S00q002:        IF laneNo_2 <= MAX_LANE_2 THEN
S01q002:                        IF detNo[ laneNo_2, 1 ] > 0 THEN
S02q002:                        Occup_2:= Occup_2+ Occup_rate( detNo[ laneNo_2, 1 ]);
S02q003:                        laneNo_2 := laneNo_2 + 1;
                                GOTO S00q002
                                END;
        END;
                Occupancy_2 := Occup_2;
                AverageOcc_2 := Occupancy_2/(MAX_LANE_2 - MAX_LANE_1);
                AvgOccup_DownStreamDet_2 := AverageOcc_2;

                Occup_1 := 0;
                Occup_2 := 0;

                OptimumFlowControlramp_1 := MeterPrevious_1 + KR*(OCC_OPT-
AvgOccup_DownStreamDet_1)*100;
                OptimumQueueControlramp_1 := ((-1/QueueCountInterval)*(W_max_o_1 -
Queue_Length_1)+RampDemandPrevious_1) ; /*arriving ramp demand*/

                IF (OptimumFlowControlramp_1>= OptimumQueueControlramp_1) THEN
                        MeterRate_1 := OptimumFlowControlramp_1;
                ELSE
                        MeterRate_1 := OptimumQueueControlramp_1;
                END;

                IF MeterRate_1 >= MaxRate THEN
                        MeterRate_1 := MaxRate;
                        RedInt_1 := (3600/MeterRate_1)*NumberMeterLane_1 - GreenInterval;
                        MeterPrevious_1 := MeterRate_1;
                ElSE
                        IF MeterRate_1 <= MinRate THEN
                                MeterRate_1 := MinRate;
                                RedInt_1 := (3600/MeterRate_1)*NumberMeterLane_1 - GreenInterval;
                                MeterPrevious_1 := MeterRate_1;
                        ELSE
                                RedInt_1 := (3600/MeterRate_1)*NumberMeterLane_1 - GreenInterval;
```

```
                    MeterPrevious_1 := MeterRate_1;
            END;
    END;

    OptimumFlowControlramp_2 := MeterPrevious_2 + KR*(OCC_OPT-
AvgOccup_DownStreamDet_2)*100;
    OptimumQueueControlramp_2 := ((-1/QueueCountInterval)*(W_max_o_2-
Queue_Length_2)+RampDemandPrevious_2) ; /*arriving ramp demand*/

    IF (OptimumFlowControlramp_2 >= OptimumQueueControlramp_2) THEN
            MeterRate_2 := OptimumFlowControlramp_2;
    ELSE
            MeterRate_2 := OptimumQueueControlramp_2;
    END;

    IF MeterRate_2 >= MaxRate THEN
            MeterRate_2 := MaxRate;
            RedInt_2 := (3600/MeterRate_2)*NumberMeterLane_2 - GreenInterval;
            MeterPrevious_2 := MeterRate_2;
    ElSE
            IF MeterRate_2 <= MinRate THEN
                    MeterRate_2 := MinRate;
                    RedInt_2 := (3600/MeterRate_2)*NumberMeterLane_2 - GreenInterval;
                    MeterPrevious_2 := MeterRate_2;
            ELSE
                    RedInt_2 := (3600/MeterRate_2)*NumberMeterLane_2 - GreenInterval;
                    MeterPrevious_2 := MeterRate_2;
            END;
    END;

    /*******Queue on Ramp**********/
    Arrival_1 :=  rear_ends(ArrivalDetector_1);
    Departure_1 :=  rear_ends(QueueDetector_Departure_1);
    Queue_Length_1 := (Arrival_1-Departure_1) + Queue_Length_Previous_1;


    IF (Queue_Length_1 > 0) THEN
            Queue_Length_1 := Queue_Length_1;
    ELSE
            Queue_Length_1 := 0;
    END;
    Queue_Length_Previous_1 := Queue_Length_1;

    RampDemand_CurrentInterval_1 := (Arrival_1)/OccupancyInterval ;
    RampDemandPrevious_1 := RampDemand_CurrentInterval_1;

    /*******Queue on Ramp**********/
    Arrival_2 :=  rear_ends(ArrivalDetector_2);
    Departure_2 :=  rear_ends(QueueDetector_Departure_2);
    Queue_Length_2 := (Arrival_2-Departure_2) + Queue_Length_Previous_2;


    IF (Queue_Length_2 > 0) THEN
            Queue_Length_2 := Queue_Length_2;
    ELSE
            Queue_Length_2 := 0;
    END;
    Queue_Length_Previous_2 := Queue_Length_2;

    RampDemand_CurrentInterval_2 := (Arrival_2)/OccupancyInterval ;
```

```
                        RampDemandPrevious_2 := RampDemand_CurrentInterval_2;

                        RESET (CountTimer);
S00b047:                laneNo_1 := 1;
S00b048:                IF laneNo_1 <= MAX_LANE_1 THEN
S01b048:                        IF detNo[ laneNo_1, 1 ] > 0 THEN
S02b048:                        clear_rear_ends( detNo[ laneNo_1, 1 ]);
S02b049:                        laneNo_1 := laneNo_1 + 1;
                                GOTO S00b048
                                END;
                END;
                        clear_rear_ends(ArrivalDetector_1);
                        clear_rear_ends(QueueDetector_Departure_1);

S00e047:                laneNo_2 := 4;
S00e048:                IF laneNo_2 <= MAX_LANE_2 THEN
S01e048:                        IF detNo[ laneNo_2, 1 ] > 0 THEN
S02e048:                        clear_rear_ends( detNo[ laneNo_2, 1 ]);
S02e049:                        laneNo_2 := laneNo_2 + 1;
                        GOTO S00e048
                                END;
                END;
                        clear_rear_ends(ArrivalDetector_2);
                        clear_rear_ends(QueueDetector_Departure_2);

                ELSE
S00b055:                laneNo_1 := 1;
S00b056:                IF laneNo_1 <= MAX_LANE_1 THEN
S01b056:                        IF detNo[ laneNo_1, 1 ] > 0 THEN
S02b056:                        Occup_1:= Occup_1+ Occup_rate( detNo[ laneNo_1, 1 ]);
S02b057:                        laneNo_1 := laneNo_1 + 1;
                                GOTO S00b056
                                END;
                END;
                        Occupancy_1 := Occup_1;
                        AverageOcc_1 := Occupancy_1/MAX_LANE_1;
                        AvgOccup_DownStreamDet_1 := AverageOcc_1;
                        Occup_1 := 0;

S00e055:                laneNo_2 := 4;
S00e056:                IF laneNo_2 <= MAX_LANE_2 THEN
S01e056:                        IF detNo[ laneNo_2, 1 ] > 0 THEN
S02e056:                        Occup_2:= Occup_2+ Occup_rate( detNo[ laneNo_2, 1 ]);
S02e057:                        laneNo_2 := laneNo_2 + 1;
                                GOTO S00e056
                                END;
                END;
                        Occupancy_2 := Occup_2;
                        AverageOcc_2 := Occupancy_2/(MAX_LANE_2 - MAX_LANE_1);
                        AvgOccup_DownStreamDet_2 := AverageOcc_2;
                        Occup_2 := 0;

                        Arrival_1 :=  rear_ends(ArrivalDetector_1);
                        Departure_1 :=  rear_ends(QueueDetector_Departure_1);
                        Queue_Length_1 := (Arrival_1-Departure_1) + Queue_Length_Previous_1;
                        IF (Queue_Length_1 > 0) THEN
                                Queue_Length_1 := Queue_Length_1;
                        ELSE
                                Queue_Length_1 := 0;
                        END;
```

```
                Arrival_2 :=  rear_ends(ArrivalDetector_2) ;
                Departure_2 :=  rear_ends(QueueDetector_Departure_2) ;
                Queue_Length_2 := (Arrival_2-Departure_2) + Queue_Length_Previous_2;

                IF (Queue_Length_2 > 0) THEN
                        Queue_Length_2 := Queue_Length_2;
                ELSE
                        Queue_Length_2 := 0;
                END;
        END.
/*********************************************************************************/
/********************************This is the main Program***************************/
/*********************************************************************************/
    START (QueueTimer);
    START (CountTimer);
    SimuTime := SimuTime + 1;
    TRACE(all);

    IF QueueTimer = (QueueCountInterval + 1) THEN
        AvgOccup_AdvanceQueueDet_1 := Occup_AdvanceQueueDet_1 / QueueCountInterval;
        QueueSpill_1 := AvgOccup_AdvanceQueueDet_1 >=Queue_Threshold;

        AvgOccup_AdvanceQueueDet_2 := Occup_AdvanceQueueDet_2 / QueueCountInterval;
        QueueSpill_2 := AvgOccup_AdvanceQueueDet_2 >=Queue_Threshold;
        RESET (QueueTimer);
        Occup_AdvanceQueueDet_1 := 0;
        Occup_AdvanceQueueDet_2 := 0;
    ELSE
        Occup_AdvanceQueueDet_1 := Occup_AdvanceQueueDet_1 + Occup_rate
(QueueDetector_Advance_1);
        Occup_AdvanceQueueDet_2 := Occup_AdvanceQueueDet_2 + Occup_rate
(QueueDetector_Advance_2);
    END;

        QMAX := Queue_Length_1/W_max_o_1;
        IF ((QMAX>Max_Threshold) AND (AvgOccup_DownStreamDet_1>0.9*Desired_Density)) THEN
                GOSUB LINKED;
                GOSUB MeterOperation2;
                GOSUB MeterOperation1;
        ELSE
                IF ((QMAX<Min_Threshold) OR (AvgOccup_DownStreamDet_1 < 0.8*Desired_Density))
THEN
                        GOSUB ALINEA;
                        GOSUB QOverride1;
                        GOSUB QOverride2;
                ELSE
                        GOSUB ALINEA;
                        GOSUB QOverride1;
                        GOSUB QOverride2;
                END;
        END.
```

APPENDIX B

Statistical Analysis Results

This appendix shows detailed results of the MANOVA and Post HOC tests performed for calibrating the ALINEA parameters. The appendix also includes all the ANOVA tests performed on each section during comparative analysis of different strategies.

Table 18
MANOVA results for ALINEA parameters calibration (east direction)

Effect		Value	F	Hypothesis df	Error df	Sig.
Intercept	Pillai's Trace	1.000	47988607.652[c]	2.000	683.000	.000
	Wilks' Lambda	.000	47988607.652[c]	2.000	683.000	.000
	Hotelling's Trace	140523.009	47988607.652[c]	2.000	683.000	.000
	Roy's Largest Root	140523.009	47988607.652[c]	2.000	683.000	.000
DetDIst	Pillai's Trace	.008	1.302	4.000	1368.000	.267
	Wilks' Lambda	.992	1.302[c]	4.000	1366.000	.267
	Hotelling's Trace	.008	1.302	4.000	1364.000	.267
	Roy's Largest Root	.008	2.571[d]	2.000	684.000	.077
OptOCC	Pillai's Trace	.001	.157	6.000	1368.000	.988
	Wilks' Lambda	.999	.157[c]	6.000	1366.000	.988
	Hotelling's Trace	.001	.157	6.000	1364.000	.988
	Roy's Largest Root	.001	.281[d]	3.000	684.000	.839
KR	Pillai's Trace	.000	.059	4.000	1368.000	.994
	Wilks' Lambda	1.000	.059[c]	4.000	1366.000	.994
	Hotelling's Trace	.000	.059	4.000	1364.000	.994
	Roy's Largest Root	.000	.107[d]	2.000	684.000	.898
DetDIst * OptOCC	Pillai's Trace	.001	.059	12.000	1368.000	1.000
	Wilks' Lambda	.999	.059[c]	12.000	1366.000	1.000
	Hotelling's Trace	.001	.059	12.000	1364.000	1.000
	Roy's Largest Root	.001	.086[d]	6.000	684.000	.998
DetDIst * KR	Pillai's Trace	.001	.047	8.000	1368.000	1.000
	Wilks' Lambda	.999	.047[c]	8.000	1366.000	1.000
	Hotelling's Trace	.001	.047	8.000	1364.000	1.000
	Roy's Largest Root	.000	.077[d]	4.000	684.000	.989
OptOCC * KR	Pillai's Trace	.000	.025	12.000	1368.000	1.000
	Wilks' Lambda	1.000	.025[c]	12.000	1366.000	1.000
	Hotelling's Trace	.000	.025	12.000	1364.000	1.000
	Roy's Largest Root	.000	.036[d]	6.000	684.000	1.000
DetDIst * OptOCC * KR	Pillai's Trace	.001	.037	24.000	1368.000	1.000
	Wilks' Lambda	.999	.036[c]	24.000	1366.000	1.000
	Hotelling's Trace	.001	.036	24.000	1364.000	1.000
	Roy's Largest Root	.001	.061[d]	12.000	684.000	1.000

Table 19
MANOVA results for ALINEA parameters calibration (west direction)

Effect		Value	F	Hypothesis df	Error df	Sig.
Intercept	Pillai's Trace	1.000	5158584.207c	2.000	683.000	.000
	Wilks' Lambda	.000	5158584.207c	2.000	683.000	.000
	Hotelling's Trace	15105.664	5158584.207c	2.000	683.000	.000
	Roy's Largest Root	15105.664	5158584.207c	2.000	683.000	.000
DetDIst	Pillai's Trace	.431	94.032	4.000	1368.000	.000
	Wilks' Lambda	.569	111.150c	4.000	1366.000	.000
	Hotelling's Trace	.756	128.900	4.000	1364.000	.000
	Roy's Largest Root	.755	258.162d	2.000	684.000	.000
OptOCC	Pillai's Trace	.007	.757	6.000	1368.000	.604
	Wilks' Lambda	.993	.756c	6.000	1366.000	.604
	Hotelling's Trace	.007	.756	6.000	1364.000	.605
	Roy's Largest Root	.006	1.315d	3.000	684.000	.268
KR	Pillai's Trace	.002	.301	4.000	1368.000	.878
	Wilks' Lambda	.998	.300c	4.000	1366.000	.878
	Hotelling's Trace	.002	.300	4.000	1364.000	.878
	Roy's Largest Root	.002	.581d	2.000	684.000	.559
DetDIst * OptOCC	Pillai's Trace	.028	1.636	12.000	1368.000	.076
	Wilks' Lambda	.972	1.637c	12.000	1366.000	.076
	Hotelling's Trace	.029	1.638	12.000	1364.000	.075
	Roy's Largest Root	.022	2.488d	6.000	684.000	.022
DetDIst * KR	Pillai's Trace	.004	.315	8.000	1368.000	.961
	Wilks' Lambda	.996	.315c	8.000	1366.000	.961
	Hotelling's Trace	.004	.314	8.000	1364.000	.961
	Roy's Largest Root	.003	.578d	4.000	684.000	.679
OptOCC * KR	Pillai's Trace	.004	.226	12.000	1368.000	.997
	Wilks' Lambda	.996	.225c	12.000	1366.000	.997
	Hotelling's Trace	.004	.225	12.000	1364.000	.997
	Roy's Largest Root	.004	.414d	6.000	684.000	.870
DetDIst * OptOCC * KR	Pillai's Trace	.019	.542	24.000	1368.000	.965
	Wilks' Lambda	.981	.541c	24.000	1366.000	.966
	Hotelling's Trace	.019	.541	24.000	1364.000	.966
	Roy's Largest Root	.013	.730d	12.000	684.000	.723

Table 20
ANOVA results for ALINEA parameters calibration (west direction)

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	VHT	6529084.312[b]	35	186545.266	11.886	.000
	Speed (MPH)	207.563[c]	35	5.930	4.117	.000
Intercept	VHT	6983951791.041	1	6983951791.041	444993.811	.000
	Speed (MPH)	1727490.734	1	1727490.734	1199371.111	.000
DetDIst	VHT	6204273.962	2	3102136.981	197.658	.000
	Speed (MPH)	177.028	2	88.514	61.454	.000
OptOCC	VHT	61663.784	3	20554.595	1.310	.270
	Speed (MPH)	4.036	3	1.345	.934	.424
KR	VHT	13158.478	2	6579.239	.419	.658
	Speed (MPH)	.361	2	.180	.125	.882
DetDIst * OptOCC	VHT	75339.515	6	12556.586	.800	.570
	Speed (MPH)	11.591	6	1.932	1.341	.236
DetDIst * KR	VHT	34551.395	4	8637.849	.550	.699
	Speed (MPH)	3.022	4	.755	.525	.718
OptOCC * KR	VHT	5447.120	6	907.853	.058	.999
	Speed (MPH)	1.959	6	.327	.227	.968
DetDIst * OptOCC * KR	VHT	134650.056	12	11220.838	.715	.738
	Speed (MPH)	9.566	12	.797	.553	.879
Error	VHT	10735032.499	684	15694.492		
	Speed (MPH)	985.186	684	1.440		
Total	VHT	7001215907.852	720			
	Speed (MPH)	1728683.482	720			
Corrected Total	VHT	17264116.811	719			
	Speed (MPH)	1192.749	719			

Table 21
Post Hoc (Tukey HSD) results for the detector distance parameter (west direction)

Dependent Variable	(I) Detector Distance	(J) Detector Distance	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
VHT	200	500	143.4732*	11.43623	.000	116.6115	170.3349
		1000	-81.0322*	11.43623	.000	-107.8939	-54.1705
	500	200	-143.4732*	11.43623	.000	-170.3349	-116.6115
		1000	-224.5054*	11.43623	.000	-251.3670	-197.6437
	1000	200	81.0322*	11.43623	.000	54.1705	107.8939
		500	224.5054*	11.43623	.000	197.6437	251.3670
Speed (MPH)	200	500	-.8111*	.10956	.000	-1.0684	-.5538
		1000	.3774*	.10956	.002	.1201	.6347
	500	200	.8111*	.10956	.000	.5538	1.0684
		1000	1.1885*	.10956	.000	.9312	1.4458
	1000	200	-.3774*	.10956	.002	-.6347	-.1201
		500	-1.1885*	.10956	.000	-1.4458	-.9312

Table 22

Post Hoc (Tukey HSD) results for the KR parameter (west direction)

Dependent Variable	(I) Kr	(J) Kr	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
VHT	60	70	6.7361	11.43623	0.826	-20.1255	33.5978
		80	-3.5752	11.43623	0.948	-30.4369	23.2865
	70	60	-6.7361	11.43623	0.826	-33.5978	20.1255
		80	-10.3113	11.43623	0.639	-37.173	16.5504
	80	60	3.5752	11.43623	0.948	-23.2865	30.4369
		70	10.3113	11.43623	0.639	-16.5504	37.173
Speed (MPH)	60	70	-0.0447	0.10956	0.912	-0.3021	0.2126
		80	0.0051	0.10956	0.999	-0.2523	0.2624
	70	60	0.0447	0.10956	0.912	-0.2126	0.3021
		80	0.0498	0.10956	0.892	-0.2075	0.3071
	80	60	-0.0051	0.10956	0.999	-0.2624	0.2523
		70	-0.0498	0.10956	0.892	-0.3071	0.2075

Table 23
Post Hoc results (Tukey HSD) for the Optimum Occupancy parameter (west direction)

Dependent Variable	(I) Optimum Occupancy	(J) Optimum Occupancy	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
VHT	.10	.20	25.5293	13.2	.215	-8.4794	59.5380
		.30	11.2379	13.2	.830	-22.7708	45.2466
		.40	16.7501	13.2	.583	-17.2586	50.7588
	.20	.10	-25.5293	13.2	.215	-59.5380	8.4794
		.30	-14.2914	13.2	.701	-48.3001	19.7173
		.40	-8.7792	13.2	.910	-42.7879	25.2295
	.30	.10	-11.2379	13.2	.830	-45.2466	22.7708
		.20	14.2914	13.2	.701	-19.7173	48.3001
		.40	5.5122	13.2	.975	-28.4965	39.5209
	.40	.10	-16.7501	13.2	.583	-50.7588	17.2586
		.20	8.7792	13.2	.910	-25.2295	42.7879
		.30	-5.5122	13.2	.975	-39.5209	28.4965
Speed (MPH)	.10	.20	-.1935	.127	.420	-.5193	.1323
		.30	-.1120	.127	.812	-.4378	.2138
		.40	-.1706	.127	.533	-.4963	.1552
	.20	.10	.1935	.127	.420	-.1323	.5193
		.30	.0815	.127	.918	-.2443	.4073
		.40	.0230	.127	.998	-.3028	.3488
	.30	.10	.1120	.127	.812	-.2138	.4378
		.20	-.0815	.127	.918	-.4073	.2443
		.40	-.0585	.127	.967	-.3843	.2673
	.40	.10	.1706	.127	.533	-.1552	.4963
		.20	-.0230	.127	.998	-.3488	.3028
		.30	.0585	.127	.967	-.2673	.3843

Table 24
ANOVA results for the comparative analysis
section = Start-Essen (east direction)

		Sum of Squares	df	Mean Square	F	Sig.
Speed (MPH)	Between Strategies	.108	2	.054	.057	.945
	Within Strategies	54.113	57	.949		
	Total	54.221	59			
Average Travel Time (seconds)	Between Strategies	.028	2	.014	.057	.945
	Within Strategies	13.911	57	.244		
	Total	13.939	59			
VHT	Between Strategies	.422	2	.211	.058	.944
	Within Strategies	206.801	57	3.628		
	Total	207.223	59			

Table 25
ANOVA results for the comparative analysis
section = Essen-Jefferson (east direction)

		Sum of Squares	df	Mean Square	F	Sig.
Speed (MPH)	Between Strategies	.096	2	.048	.463	.632
	Within Strategies	5.920	57	.104		
	Total	6.016	59			
Average Travel Time (seconds)	Between Strategies	.048	2	.024	.479	.622
	Within Strategies	2.857	57	.050		
	Total	2.905	59			
VHT	Between Strategies	.608	2	.304	.382	.685
	Within Strategies	45.453	57	.797		
	Total	46.061	59			

Table 26
ANOVA results for the comparative analysis
section = Jefferson-Airline (east direction)

		Sum of Squares	df	Mean Square	F	Sig.
Speed (MPH)	Between Strategies	29.826	2	14.913	1.101	.339
	Within Strategies	771.889	57	13.542		
	Total	801.715	59			
Average Travel Time (seconds)	Between Strategies	27.828	2	13.914	1.009	.371
	Within Strategies	786.258	57	13.794		
	Total	814.086	59			
VHT	Between Strategies	545.595	2	272.797	1.009	.371
	Within Strategies	15403.16	57	270.231		
	Total	15948.75	59			

Table 27
ANOVA results for the comparative analysis
Section = Airline-Sherwood (east direction)

		Sum of Squares	df	Mean Square	F	Sig.
Speed (MPH)	Between Strategies	14.199	2	7.100	0.799	.459
	Within Strategies	513.257	57	9.005		
	Total	527.456	59			
Average Travel Time (seconds)	Between Strategies	54.687	2	27.344	.794	.457
	Within Strategies	1963.032	57	34.439		
	Total	2017.719	59			
VHT	Between Strategies	1062.445	2	531.223	.813	.449
	Within Strategies	37233.937	57	653.227		
	Total	38296.382	59			

Table 28
ANOVA results for the comparative analysis
section = Sherwood-Millerville (east direction)

		Sum of Squares	df	Mean Square	F	Sig.
Speed (MPH)	Between Strategies	.139	2	.069	.430	.652
	Within Strategies	9.204	57	.161		
	Total	9.343	59			
Average Travel Time (seconds)	Between Strategies	.523	2	.262	.441	.646
	Within Strategies	33.849	57	.594		
	Total	34.372	59			
VHT	Between Strategies	3.623	2	1.812	.099	.906
	Within Strategies	1048.320	57	18.392		
	Total	.139	2	.069	.430	.652

Table 29
ANOVA results for the comparative analysis
section = Millerville-O'Neal (east direction)

		Sum of Squares	df	Mean Square	F	Sig.
Speed (MPH)	Between Strategies	.118	2	.059	.045	.956
	Within Strategies	74.014	57	1.298		
	Total	74.132	59			
Average Travel Time (seconds)	Between Strategies	.256	2	.128	.062	.940
	Within Strategies	116.922	57	2.051		
	Total	117.178	59			
VHT	Between Strategies	.798	2	.399	.010	.990
	Within Strategies	2231.698	57	39.153		
	Total	2232.496	59			

Table 30
ANOVA results for the comparative analysis
section = O'Neal-Range (east direction)

		Sum of Squares	df	Mean Square	F	Sig.
Speed (MPH)	Between Strategies	.044	2	.022	.281	.756
	Within Strategies	4.481	57	.079		
	Total	4.525	59			
Average Travel Time (seconds)	Between Strategies	.365	2	.182	.284	.754
	Within Strategies	36.597	57	.642		
	Total	36.961	59			
VHT	Between Strategies	4.625	2	2.313	.168	.846
	Within Strategies	784.972	57	13.771		
	Total	789.597	59			

Table 31
ANOVA results for the comparative analysis
section = Range-Juban (east direction)

		Sum of Squares	df	Mean Square	F	Sig.
Speed (MPH)	Between Strategies	.128	2	.064	2.077	.135
	Within Strategies	1.757	57	.031		
	Total	1.885	59			
Average Travel Time (seconds)	Between Strategies	.597	2	.299	2.073	.135
	Within Strategies	8.211	57	.144		
	Total	8.808	59			
VHT	Between Strategies	4.752	2	2.376	.233	.793
	Within Strategies	581.335	57	10.199		
	Total	586.087	59			

Table 32
ANOVA results for the comparative analysis
section = Juban-Walker (east direction)

		Sum of Squares	df	Mean Square	F	Sig.
Speed (MPH)	Between Strategies	.001	2	.001	.780	.463
	Within Strategies	.054	57	.001		
	Total	.056	59			
Average Travel Time (seconds)	Between Strategies	.012	2	.006	.780	.463
	Within Strategies	.444	57	.008		
	Total	.456	59			
VHT	Between Strategies	.552	2	.276	.012	.988
	Within Strategies	1350.026	57	23.685		
	Total	1350.578	59			

Table 33
ANOVA results for the comparative analysis
section = Walker-End (east direction)

		Sum of Squares	df	Mean Square	F	Sig.
Speed (MPH)	Between Strategies	.000	2	.000	.474	.625
	Within Strategies	.007	55	.000		
	Total	.007	57			
Average Travel Time (seconds)	Between Strategies	.000	2	.000	.473	.625
	Within Strategies	.008	55	.000		
	Total	.008	57			
VHT	Between Strategies	1.331	2	.665	.190	.827
	Within Strategies	192.267	55	3.496		
	Total	193.597	57			

Table 34
ANOVA results for the comparative analysis
section = Start-Walker (west direction)

		Sum of Squares	df	Mean Square	F	Sig.
Speed (MPH)	Between Strategies	.000	2	.000	.006	.994
	Within Strategies	.110	57	.002		
	Total	.110	59			
Average Travel Time (seconds)	Between Strategies	.000	2	.000	.006	.994
	Within Strategies	.132	57	.002		
	Total	.132	59			
VHT	Between Strategies	.001	2	.001	.002	.998
	Within Strategies	12.056	57	.212		
	Total	12.057	59			

Table 35
ANOVA results for the comparative analysis
section = Walker-Juban (west direction)

		Sum of Squares	df	Mean Square	F	Sig.
Speed (MPH)	Between Strategies	.001	2	.000	.853	.431
	Within Strategies	.027	57	.000		
	Total	.028	59			
Average Travel Time (seconds)	Between Strategies	.007	2	.003	.854	.431
	Within Strategies	.218	57	.004		
	Total	.224	59			
VHT	Between Strategies	.142	2	.071	.025	.976
	Within Strategies	163.696	57	2.872		
	Total	163.838	59			

Table 36
ANOVA results for the comparative analysis
section = Juban-Range (west direction)

		Sum of Squares	df	Mean Square	F	Sig.
Speed (MPH)	Between Strategies	1.051	2	.526	9.321	.000
	Within Strategies	3.214	57	.056		
	Total	4.265	59			
Average Travel Time (seconds)	Between Strategies	5.610	2	2.805	9.337	.000
	Within Strategies	17.126	57	.300		
	Total	22.736	59			
VHT	Between Strategies	15.475	2	7.737	2.104	.131
	Within Strategies	209.579	57	3.677		
	Total	225.054	59			

Table 37
ANOVA results for the comparative analysis
section = Range-O'Neal (west direction)

		Sum of Squares	df	Mean Square	F	Sig.
Speed (MPH)	Between Strategies	377.697	2	188.849	13.550	.000
	Within Strategies	794.407	57	13.937		
	Total	1172.104	59			
Average Travel Time (seconds)	Between Strategies	18433.025	2	9216.512	12.387	.000
	Within Strategies	42410.151	57	744.038		
	Total	60843.176	59			
VHT	Between Strategies	85954.876	2	42977.438	12.740	.000
	Within Strategies	192281.331	57	3373.357		
	Total	278236.207	59			

Table 38
ANOVA results for the comparative analysis
section = O'Neal-Millerville (west direction)

		Sum of Squares	df	Mean Square	F	Sig.
Speed (MPH)	Between Strategies	1886.360	2	943.180	9.206	.000
	Within Strategies	5839.842	57	102.453		
	Total	7726.201	59			
Average Travel Time (seconds)	Between Strategies	11791.703	2	5895.852	8.478	.001
	Within Strategies	39637.188	57	695.389		
	Total	51428.891	59			
VHT	Between Strategies	101098.100	2	50549.050	8.800	.000
	Within Strategies	327403.684	57	5743.924		
	Total	428501.783	59			

Table 39
ANOVA results for the comparative analysis
section = Millerville-Sherwood (west direction)

		Sum of Squares	df	Mean Square	F	Sig.
Speed (MPH)	Between Strategies	45.756	2	22.878	1.943	.153
	Within Strategies	671.121	57	11.774		
	Total	716.877	59			
Average Travel Time (seconds)	Between Strategies	2751.358	2	1375.679	2.501	.091
	Within Strategies	31349.168	57	549.985		
	Total	34100.526	59			
VHT	Between Strategies	48756.26	2	24378.134	3.839	.027
	Within Strategies	361939.62	57	6349.818		
	Total	410695.88	59			

Table 40
ANOVA results for the comparative analysis
section = Airline-Jefferson (west direction)

		Sum of Squares	df	Mean Square	F	Sig.
Speed (MPH)	Between Strategies	4.522	2	2.261	.257	.775
	Within Strategies	502.112	57	8.809		
	Total	506.634	59			
Average Travel Time (seconds)	Between Strategies	16.477	2	8.239	.255	.776
	Within Strategies	1842.399	57	32.323		
	Total	1858.876	59			
VHT	Between Strategies	276.362	2	138.181	.299	.743
	Within Strategies	26326.305	57	461.865		
	Total	26602.668	59			

Table 41
ANOVA results for the comparative analysis
section = Jefferson-Essen (west direction)

		Sum of Squares	df	Mean Square	F	Sig.
Speed (MPH)	Between Strategies	.025	2	.013	.414	.663
	Within Strategies	1.731	57	.030		
	Total	1.756	59			
Average Travel Time (seconds)	Between Strategies	.016	2	.008	.412	.665
	Within Strategies	1.087	57	.019		
	Total	1.102	59			
VHT	Between Strategies	43.983	2	21.991	13.548	.000
	Within Strategies	92.526	57	1.623		
	Total	136.509	59			

Table 42
ANOVA results for the comparative analysis
section = Essen-End (west direction)

		Sum of Squares	df	Mean Square	F	Sig.
Speed (MPH)	Between Strategies	1.607	2	.803	.821	.445
	Within Strategies	53.836	55	.979		
	Total	55.442	57			
Average Travel Time (seconds)	Between Strategies	.323	2	.161	.839	.437
	Within Strategies	10.573	55	.192		
	Total	10.895	57			
VHT	Between Strategies	3.051	2	1.526	.376	.689
	Within Strategies	1.607	2	.803	.821	.445
	Total	53.836	55	.979		