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Quantifying Operational Impacts of Variations in Work Zone Setups, Traffic Demand, and Traffic Composition: A Case Study

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Abstract

The presence of work zones due to pavement repair and rehabilitation is very common in highway facilities. Lane closures associated with work zones result in capacity reduction, which, in turn, often leads to increased congestion at such locations. This paper documents findings from a study that investigated the performance of freeway facilities in the presence of work zones under various Temporary Traffic Control (TTC) and lane closure scenarios while taking under consideration traffic composition and driving behaviors. The study site was an approximately 10-mile freeway segment of Interstate 65 (I-65) located in Birmingham, AL. The testbed was coded in PTV VISSIM, a microscopic simulation analysis platform, for: 1) baseline conditions (*i.e.*, no work zone presence) and 2) work zone conditions with single lane closure (*i.e.*, 3-to-2 lane closure). Work zone scenarios were coded for two TTC strategies, namely, early merge and late merge control and for three different positions of the lane closure (*i.e.*, left, right, and center lane closures). The length of the work zones varied from 1000 to 2000, and 3000 ft. Sensitivity analysis was performed to document the operational impacts of varying heavy vehicle percentages, changes in drivers' aggressiveness, and projected traffic demand changes. The impacts were quantified using linked-based measures of effectiveness (MOEs) such as travel time, and travel time index. The study results show that there is no significant change in travel time index due to the variation of work zone length across the study corridor. Under similar traffic control and demand conditions, a center lane closure consistently results in significantly higher travel time index than a left or right lane closure and should be avoided. Consideration of operational impacts of changes in truck percentage indicates that the corridor can absorb an increase in truck percentage from 10% to 15%, while performance rapidly deteriorates when a higher percentage of trucks is present in the traffic stream. The study findings can be used to guide transportation agencies in their future efforts to develop strategic lane closure plans that minimize congestion.

Keywords

Work Zone Placement, Late Merge Control, PTV VISSIM

1. Introduction

As transportation agencies focus their efforts on highway system maintenance and preservation, the presence of work zones on the nation's highways is increasingly prevalent. While work zones and the requisite temporary traffic control (TTC) provide a location for construction and maintenance activities to occur, work zones also impact the mobility and safety of the traveling public. It is expected that a driver will face at least one active work zone out of every 100 miles driven on the freeway [1]. Earlier research estimated that the presence of a work zone contributes to approximately 24% of the non-recurring delays, making work zones the second most significant cause of non-recurring delay on freeways [2].

Short term work zone activities for maintenance and rehabilitation of pavement often require lane closures. This forces traffic to merge into adjacent open lanes and often leads to reduction of available capacity, disruption in normal traffic flow conditions, and traffic congestion [3]. In addition to their impacts on traffic operations, work zone lane closures appear to increase the total crash rate by as much as 21.5%, thus requiring drivers to exhibit extra alertness while driving through work zones [2] [4].

The Federal Highway Administration (FHWA) rule includes many performance measures for evaluating operational performance [5]. However, there is a lack of specific performance measures for accessing congestion under special events, including the presence of work zones under different design and traffic control configurations [6]. Earlier studies suggest that the impacts of short-term work zone lane closures resemble those of lane closures due to incidents where the reduction of capacity depends on the number of lanes that are closed as well as the total number of lanes affected [7].

The literature confirms that the most commonly employed Temporary Traffic Control (TTC) strategy at work zone merge locations is early merge, followed by late merge traffic control [8]. However, a 2015 national survey of practice from 27 State DOTs revealed that most State Departments of Transportation (DOTs) attribute the choice of work zone merge control strategy to earlier experience within their agency, rather than consideration of potential operational or safety impacts. Furthermore, earlier studies confirm that there is a lack of systematic methods and guidelines for operational assessment of various work zone configurations in freeway settings [6] [8].

Thus, there is a need to analyze the impact of lane drop placement on work zone performance while considering variations in work-zone length, work zone scheduling period, and traffic control strategies. Although research has been done on late merge and early merge control strategy for work zones, the effects of right lane versus left lane closure under those temporary traffic control strategies have not been adequately assessed.

The purpose of this study is to examine mobility impacts of various combinations of lane closures, TTC strategies, and work zone lengths and identify those combinations that will have minimal impacts on mobility. Microscopic traffic simulation modeling is used to examine and quantify such impacts. The study findings are expected to provide valuable guidance for agencies responsible for planning, design, and operations of work zones.

2. Literature Review

2.1. Effect of Lane Closure Geometrics in Work Zone

Early merge and late merge control strategies are commonly used strategies to manage traffic for work zone late closures. The early merge control strategy is a technique used at work zone locations where vehicles are encouraged to merge into open lanes way ahead from the lane closure location with advance warning signs. This set up gives drivers that are approaching a work zone advanced information about which lane is closed and enough time to merge in the open lane(s). On the other hand, the late merge or zipper merge traffic control strategy is a merging scenario where drivers that are approaching a work zone use all travel lanes up to the starting point of the tapered portion of the work zone. This way, the road space can be used up to the merge point of the work zone, thus increasing the operational efficiency of the roadway [9].

Several studies investigated driver behaviors in the presence of work zones. Some studies found that drivers do not usually obey the temporary speed limit in work zones, and they reduce speeds only when the lane width is reduced [10]. Driving behaviors are influenced more by the visual perception of physical constraints rather than by temporary speed limit signs. A study [10] that analyzed the speed distribution in a two-lane highway with a work zone revealed that without a physical reduction of the carriage width and with a temporary speed limit of 18.6 mph (30 km/hr), more than 80 percent of the vehicles exceeded the temporary speed limit. For this reason, the Manual on Uniform Traffic Control Devices (MUTCD) [11] recommends using a transition area that is the section of highway where vehicles are redirected out of their normal path to enforce the reduced temporary speed limit.

Geometric features that can affect the capacity of the work zone include the number of lanes that are closed, lane widths, existence of divided lanes, longitudinal gradient, orientation of closure (left or right lane) and location of the work zone (*i.e.*, rural versus urban areas) [12]. In 2004, the Michigan Department of Transportation in collaboration with the Wayne State University performed research on 3-to-2 lane closure involving a work zone with variation in lane closure orientation (*i.e.*, right lane closure and left lane closure). Floating car method was used to perform travel time and delay studies for the study site. The study developed a Dynamic Early Lane Merge Traffic Control System (DELMTCS) plan for 3-to-2 lane closure scenario. The travel time and delay results from before and after the implementation of DELMTCS indicated a statistically significant reduction in travel times and delays encountered during the morning peak due to DELMTCS. Results showed that DELMTCS could efficiently handle the traffic volume of approximately 1500 vphpl to 1750 vphpl without experiencing extreme level of congestion [13].

In another study, the University of Nebraska examined Pennsylvania DOT's late merge control strategy where analysis of field tests of 2-to-1 lane reduction scenario concluded that the use of the late merge resulted in 75% fewer forced merges and a capacity increase of 1470 passenger cars per hour (pcph), versus 1340 (pcph) for the static early merge [14]. Furthermore, the Texas Transportation Institute (TTI) performed a study on 3-to-2 lane closure scenario with a late merge control strategy and found that the application of late merge strategy can delay the onset of congestion at the work zone by 14 min [14].

2.2. Effect of Truck Percentage and Driving Behavior Variation in Work Zone

A study by Yuan *et al.* [15] compared the performance of Lane Based Signal Merge (LBSM) control strategy at the volume level of 1000 vphpl under various heavy vehicle percentages. The testbed was developed in the VISSIM simulation platform and compared the performance of the work zone under LBSM, early, and late merge strategies. The research concluded that when the truck percentage reaches 20%, there is heavy congestion at the work zone, and among the various TTC studied, late merge yields significantly higher throughputs than other TTC options [14].

It should be also noted that the reduction in the number of travel lanes at work zones often leads to changes in driving behaviors. However, the literature search shows a lack of studies to adequately address the relationship between traffic demand and driver behavior at work zones [16].

In 2015, Ramadan and Sisiopiku surveyed State DOTs across the US and Canada to document common practices related to traffic control at work zones [8]. Results from the study confirmed that lane closures due to maintenance work are typically scheduled during the off-peak periods (nighttime). More than half of the DOTs surveyed reported implementing static early merge traffic control, whereas 20% used static late merge control. According to the survey responses, most transportation agencies admitted relying on past experience and convenience for selecting the merge control strategy in the work zone set up, rather than the use of formal criteria or the consideration of potential operational efficiency improvements and safety impacts.

Furthermore, change in percentage of heavy vehicles and driver population in work zones can create a significant variation in freeway performance, even on the same day and same construction site [17]. Thus, such factors need to be considered when the performance of work zones is investigated.

3. Study Objective

In order to address current literature gaps, this study uses a case study to examine the performance of freeway facilities in the presence of work zones under various Temporary Traffic Control (TTC) and lane closure scenarios while taking under consideration traffic composition and driving behaviors.

4. Methodology

4.1. Approach

This study employed microsimulation modeling in order to analyze and compare various scenarios. Simulation modeling is a popular and effective technique for analyzing a wide variety of transportation problems which are complex and cannot be described in mathematical or logical forms. Simulation models are designed to replicate closely the behavior and interactions of real-world system components in a controlled environment. Properly designed simulation models utilize computer software to produce detailed, quantitative description of system performance thus allowing evaluation of operational performance, comparison of alternatives, and testing of new designs and new concepts in a safe and efficient manner [18].

In this study, we performed a comparison among popular microsimulation models in order to identify and select an appropriate software for the purposes of the study. Table 1 summarizes features, advantages, and shortcomings of the

Table 1. Comparison of popular simulation platforms features.

Modeling Platform	Advantage	Disadvantage
SIDRA	Suitable for projects with tight time frames and smaller budget	Not capable of simulating all the effects of upstream and downstream of an intersection
AIMSUN	Models with ramp metering are easier to set up in AIMSUN	Cannot efficiently simulate Gipps-based models
VISSIM	Can integrate both car following behavior and lane changing logic in a traffic stream	Requires a lot of data inputs, more time and effort to develop a model
CORSIM	Capable to simulate signal systems, highway systems, freeway system and combined signal	Can cause in correct output at high on-ramp volume with metering
MATSIM	Provides a framework for demand-modeling and agent-based mobility-simulation	Inability to incorporate real-time data to make accurate short-term predictions
SIMTRAFFIC	Very user friendly and less complicated	Lacks in supporting detailed output of vehicle-state variable information

most popular software packages available for traffic simulation of transportation facilities as documented in the literature. Based on the findings from the micro-simulation model comparison, we selected VISSIM as the simulation platform in this study for its superiority and ability to meet the study goals and needs. VISSIM is a microscopic, stochastic, multi-modal simulation model that was developed in Karlsruhe, Germany, by Planning Transport Verkehr (PTV) [19] [20]. PTV VISSIM distributes the software in the United States. Details about the software are available at the VISSIM User Manual 10 [21].

4.2. Study Site Description

An approximately 10-mile segment of Interstate 65 (I-65) that runs through Birmingham, AL was selected as the study testbed. The segment is located between Exits 247 and 258. The facility has three 12-ft wide traffic lanes in both the northbound (NB) and southbound (SB) directions, with occasional acceleration and deceleration lanes added near ramps. The posted speed limit is 60 mph along the corridor mainline and 45 mph on-ramps.

The work zone is set up on the NB direction between Exits 252 and 254 in all experiments conducted as part of this study. Locating the work zone near the center of the study corridor allows for observation of spillback effects upstream of the work zone location. **Figure 1** shows a schematic of the study corridor location.

4.3. Traffic Data

Traffic volume data for the mainline corridor were obtained from the Alabama Department of Transportation (ALDOT) for Thursday, April 19, 2018, a typical weekday. The data were documented on an hour-by-hour basis over a 24-hr period. On-ramp and off-ramp volumes were also provided by ALDOT. It should be noted that ALDOT does not have permanent detectors on all ramps but collects ramp volumes periodically, so counts were not available on April 19, 2018 for several ramps. Thus, we had to rely on ramp counts obtained from other days in 2018. As a result, some traffic volumes did not balance, and adjustments had to take place to on- and/or off-ramp volumes to ensure that the volumes were balanced, and no vehicles were lost along the corridor.

ArcGIS shapefiles were obtained from the Regional Planning Commission of Greater Birmingham (RPCGB). The raw data from ALDOT and shapefiles from RPCGB were cross-checked to confirm that no traffic counter remained unidentified. Given the lack of specific details about the truck use of the study corridor, the traffic composition was assumed to be 10% trucks and 90% passenger vehicles throughout the simulation experiments.

4.4. Experimental Design

The experimental design for this study included the development of a baseline model for 24-hr traffic demand and models with work zone presence representing

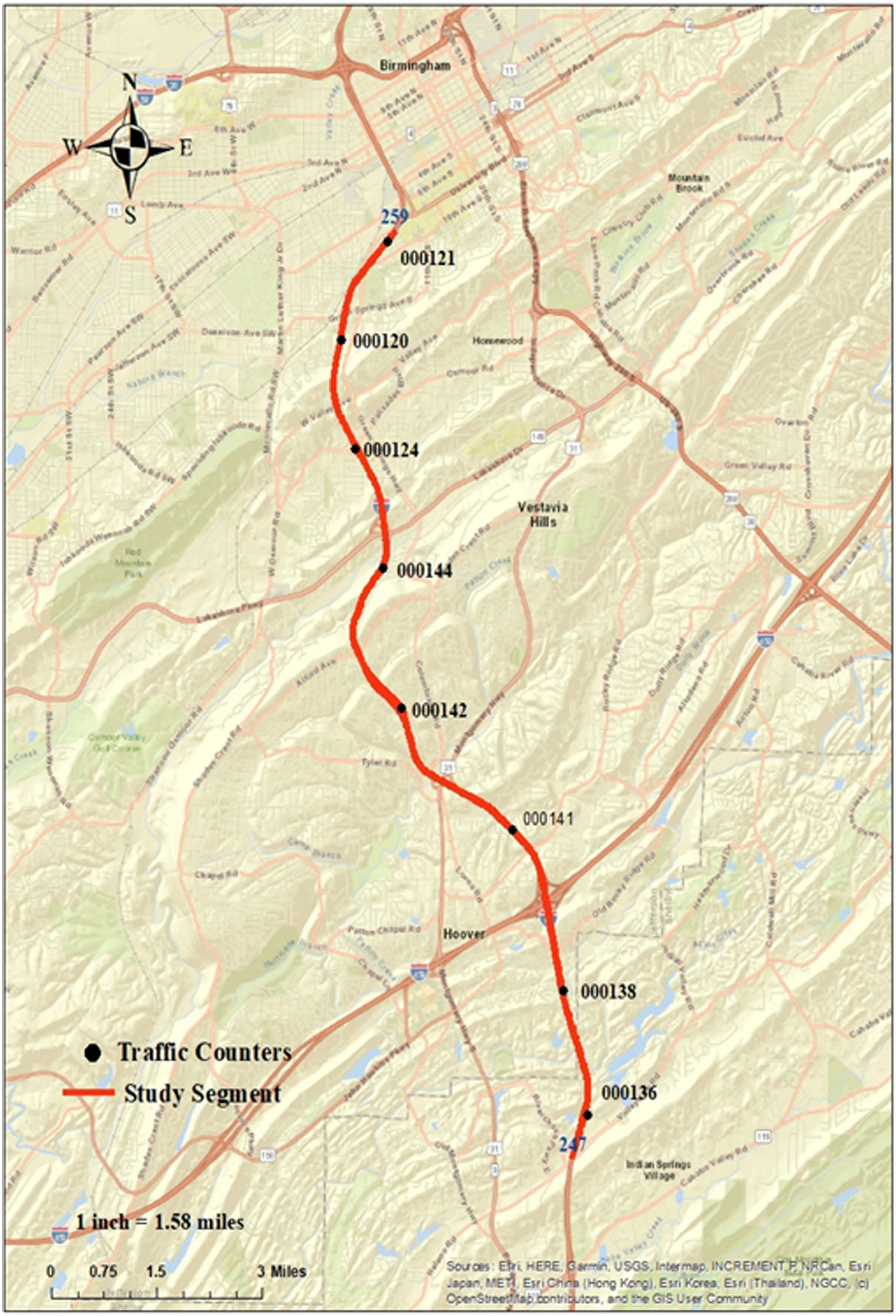

Figure 1. I-65 study corridor.

a combination of different options of TTC strategy, lane closure placement, and work zone length. In this study, we considered late merge TTC option, three work zone locations (*i.e.*, right, left, and middle lane closures), and three work-space lengths (*i.e.*, 1000, 2000, and 3000 ft). The base model was coded for 10% heavy vehicles and 90% passenger cars.

Moreover, changes in traffic composition and traffic volume were considered. Along these lines, a sensitivity analysis was performed by changing the truck percentage (from 10% to 25% in increments of 5%) both in the base model and the work zone models and evaluating operational impacts. For the latter, a 3000 ft work zone model operating under late merge control with a left lane closure was selected for assessing the impact of variations in truck percentage.

4.5. Coding Work Zones into VISSIM

The VISSIM platform does not provide an option by which a user can directly specify a lane closure in the network to represent work zone operations. So, the lane closure scenarios were coded by introducing an event that has a similar operational effect. For modeling the right and left lane drop under the 3-to-2 lane drop configuration, a connector was used over the link, and then partial routing and static routing decisions were provided simultaneously. The length of the connector was selected according to the extent of the work zone configuration. Due to the coding of the routing decision, vehicles were warned about the work zone ahead and recognized that they needed to merge.

The length of the connector was equal to that of the work zone. The MUTCD guidelines [11] were used for encrypting the buffer zones before the start of the work zone into the model. The emergency stoppage distance from the work zone for the late merge was coded as 100 ft upstream to ensure that vehicles are forced to merge at this point. This enforcement of the point of merge for late merge strategy helped to compare results generated from early merge control strategy with same length of road closure. The point of merge initiation was coded with the help of the routing decision tool in VISSIM. The look ahead distance (1640.42 ft) was taken as the default value coded in the VISSIM and the driving behaviors for all the upstream and downstream links of the work zone location were assumed to be similar to those for default freeway (free lane selection).

Center lane drop in a 3-lane freeway is less common during construction, and the literature review confirmed a lack of in-depth studies assessing a condition where the middle lane was blocked in a freeway. Although rare, there are cases in real life where the transportation authority needs to close the center lane and divert the traffic into the leftmost and/or rightmost lane. Thus, we investigated a 3-to-2 lane closure of the center lane and evaluated its impacts on operational performance. In doing so, the center lane closure was coded like a zipper merge scenario where the width of the lane gradually decreased, forcing the drivers to merge into the rightmost or leftmost lanes. Modeling for the center lane closure was really tricky as the routing decision was different. The routing decision of the center lane was coded dynamically with a formula. The "IF" function was used to ensure that 50% vehicles traveling in the center lane will merge into the rightmost lane, and 50% of the vehicles traveling in the center lane will merge into the leftmost lane.

4.6. Calibration and Validation

The parameters associated with car-following behavior, lane changing behavior, and lateral driving behavior were adjusted in order to mimic field driving condition by trial-and-error process. Earlier research [20] found that parameters related to car-following behaviors had greater impact on work zone throughput compared to parameters for lane changing model. To pass the validation and calibration test, the 24-hour travel time output from VISSIM was compared to the National Performance Management Research Data Set (NPMRDS) field data and had to fall within 15 percent range of the actual travel time values. This range demonstrates the tolerance of acceptability and is deemed reasonable for traffic studies based on earlier efforts reported in the literature and engineering judgment [19].

Figure 2 shows the comparison of total travel times resulting from VISSIM for 24 hours along the corridor with actual field data. Travel time results from the VISSIM output fall within the upper lower tolerance limits (±15%). The findings from the comparison provide confidence that the baseline model coded in VISSIM is replicating closely the realfield conditions.

After the calibration and validation steps were completed for the baseline model, various work zone models were developed according to the experimental design plan and used to perform further analysis.

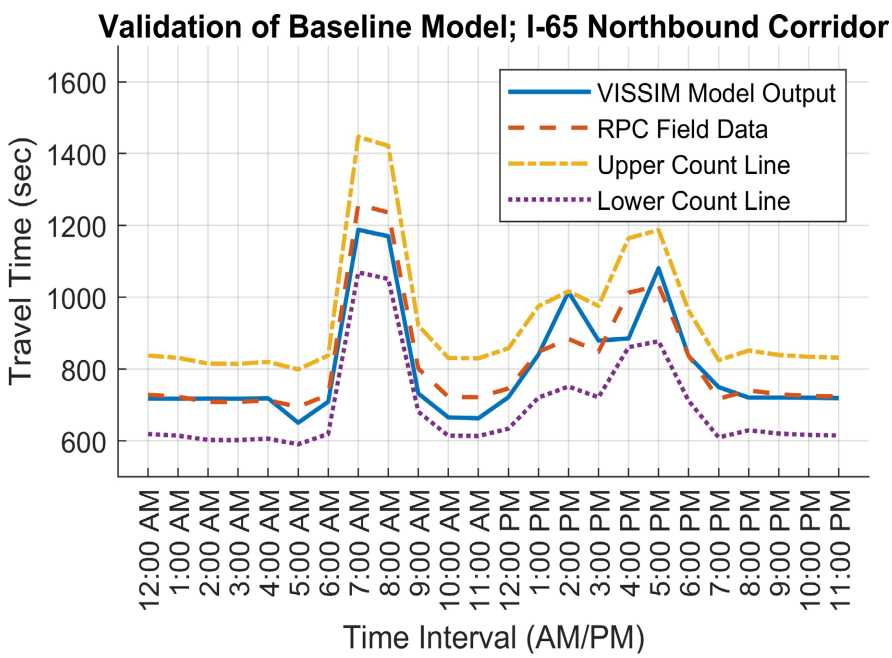

Figure 2. Validation of baseline model; I-65 northbound corridor.

5. Data Analysis and Results

In this study, simulation modeling and data analysis account for changes in geometrics (lane position, length of work zone) and variations in volume and traffic composition. Results from the work zone simulation models were compared with those from the base model which represents normal condition in order to determine how the performance of the corridor changes with change in any geometrics, control type, and traffic composition in the presence of work zones.

Measures of effectiveness (MOE) considered are travel time, and travel time index along the corridor. Travel time is the average time (in secs) it takes a vehicle to travel along the study corridor. Travel time index is defined as the % change in travel time between the work zone scenario and the baseline scenario and is calculated as follows for each hour:

$$I_T = \left(\left(T_S - T_B\right)/T_B\right) \times 100$$

where:

I_T = Travel Time Index;

T_B = Hourly travel time along the corridor for the baseline scenario "B" and;

T_S = Hourly travel time along the corridor within the defined work zone scenario "S".

5.1. Effect of Length of Work Zone

To investigate the potential effect of work zone length, the study corridor was coded into the VISSIM platform according to the experimental design plan for work zone lengths of 1000 ft, 2000 ft and 3000 ft for late merge control strategies. The results for the impact of the length of the lane closures are shown in **Figure 3** and **Figure 4** in terms of I_T-Travel time index on an hour-by-hour basis.

Close examination of the simulation results revealed that the variation of travel time index due to the change of work zone length was negligible. This is consistent with earlier findings by Ramadan and Sisiopiku [6] [8]. No statistical analysis was performed as the visual interpretation of the results was deemed sufficient. Based on these findings, and since there is no significant change in results due to work zone length variation, the following paragraphs concentrate on results from lane closures of 3000 ft length only.

5.2. Impact of Work Zone Lane Closure over Space

The study investigated how travel time index (I_T) varied over time and over space along the 10-mile long study corridor due to work zone presence under the various lane closure positions (right-most, center, and left-most lane closure). The late merge control strategy for left, center, and right lane closure of 3000 ft was selected for demonstration purposes. Each roadway segment is defined by a unique identifier known as the TMC (Traffic Message Channel) code. The entire study segment was divided into 20 TMC influence areas, and travel

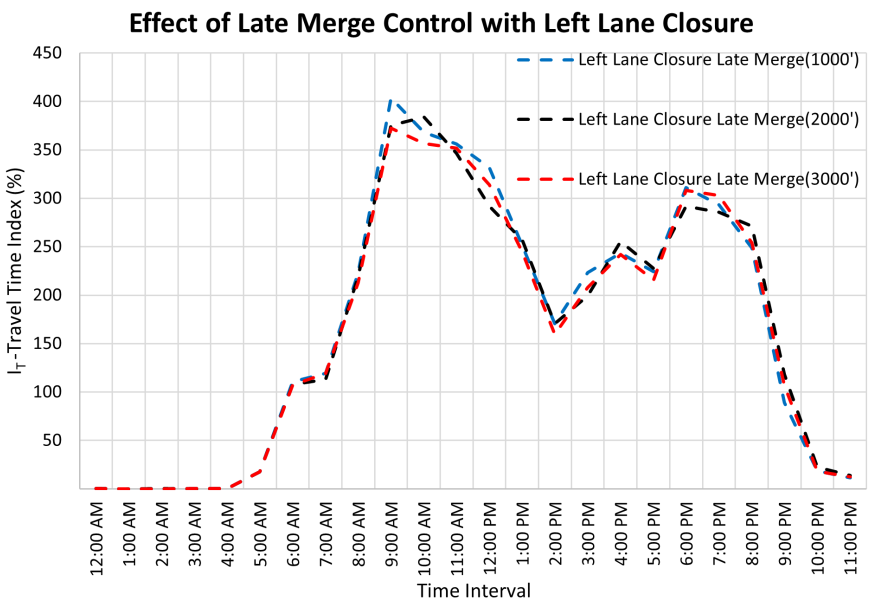

Figure 3. Effect of lane closure length-late merge; left lane closure.

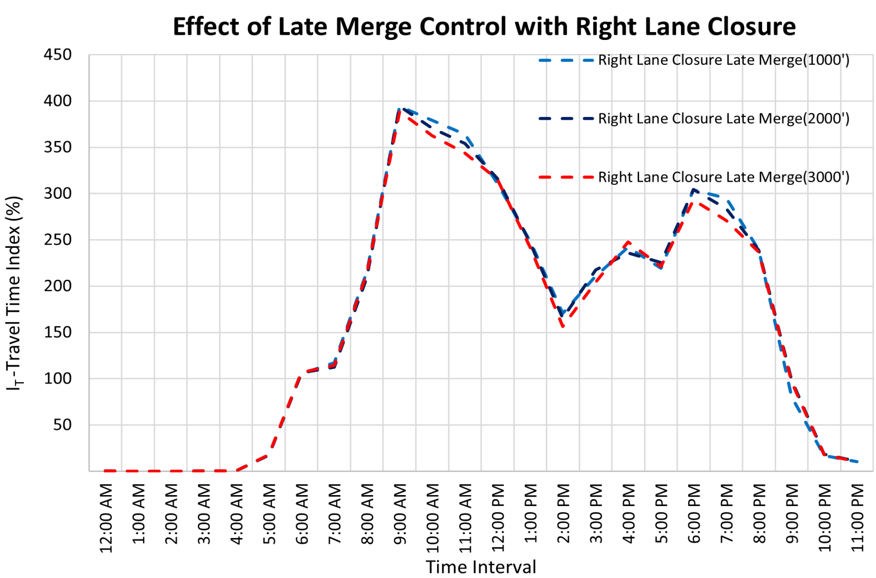

Figure 4. Effect of lane closure length-late merge; right lane closure.

time index (I_T) were obtained for peak and non-peak hours of the day by TMC. Work zones were set up in TMCs 5, 6, and 7. Sample results for 8 am (peak hour) and 2 pm (off-peak hour) are shown in Figure 5 and Figure 6, respectively.

Figure 5 shows the travel time index (I_T) for left, center, and right lane closure at 8 am peak traffic hour for vehicles traveling northbound along the I-65 study corridor. It can be observed that the operational performance of the corridor (expressed in terms of I_T) under the left and right lane closure assumption is pretty similar. However, the I_T values for center lane closure are significantly higher upstream of the work zone location where vehicles are trying to find a

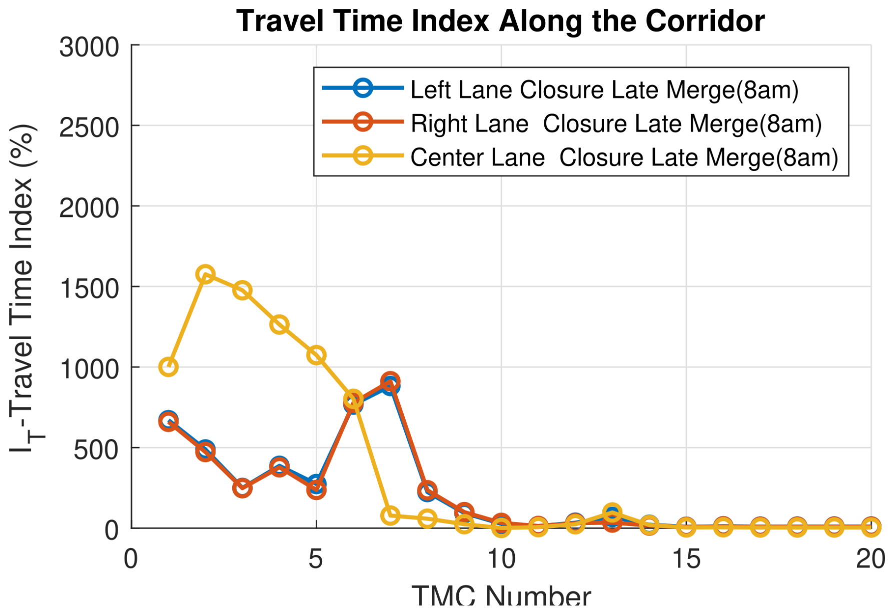

Figure 5. Travel time index (I_T) at 8 am along the corridor due to 3000 ft (left, right and center) lane closure.

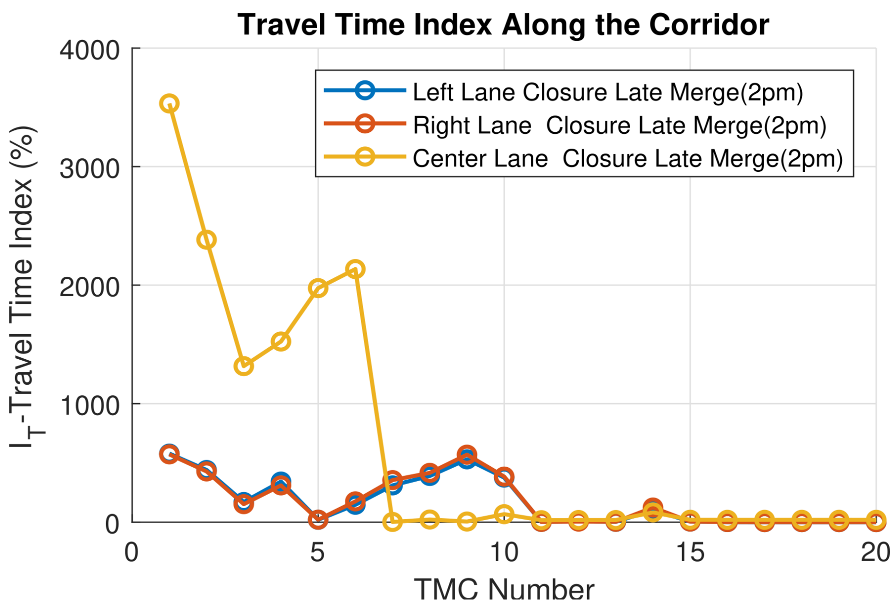

Figure 6. Travel time index (I_T) at 2 pm along the corridor due to 3000 ft (left, right and center) lane closure.

gap to merge into an open right or left lane.

Figure 6 shows I_T for left, center, and right lane closure at 2 pm, a time period that represents non-peak conditions for vehicles traveling northbound. The operational performance of the corridor with a left or a right lane closure along the corridor is very similar. As far as the center lane closure is concerned, Figure 6 shows a dramatic spike in travel time index (I_T) immediately upstream of the work zone. Higher travel time and delays are expected when closing a center lane due to the number of merges involved at the bottleneck, however, the results obtained for the center lane scenario appear unrealistic and thus caution is recommended in generalizing these results before more detailed work is done to address modeling issues related to middle lane closures. This is likely the reason that the literature does not document results from simulation studies investigating the center lane closure impacts in detail.

5.3. Impact of Lane Closure Location (Left, Center, Right)

The impact of the position of the lane closure was evaluated on the basis of travel time index (I_T) as shown in **Figure 7**. The figure displays a comparison of travel time index for 24 hours for varying lane closure position strategy (*i.e.*, left, center, and right lane closure) operating under a late merge control strategy.

As seen from **Figure 7**, the operational performance of the corridor worsens in the presence of work zones, but it is similar between closing a right-most or left-most lane. However, a center lane closure results in significant increase in travel time index, especially around peak times. Another observation is that in the presence of right or left lane closures, congestion developed during the peak period can recover during non-peak periods. But the congestion in peak period due to center lane closure is so high that it carries into the subsequent hours, and the corridor remains overwhelmed by excessive demand and cannot fully recover even during the off-peak hours.

5.4. Effect of Increased Volume

The simulation models were run with 10%, 20%, and 30% increase in traffic volume in an effort to investigate how the corridor performs with the increased traffic demand. The operational performance of the base model and work zone model in terms of Travel Time under increase in traffic demand are compared in

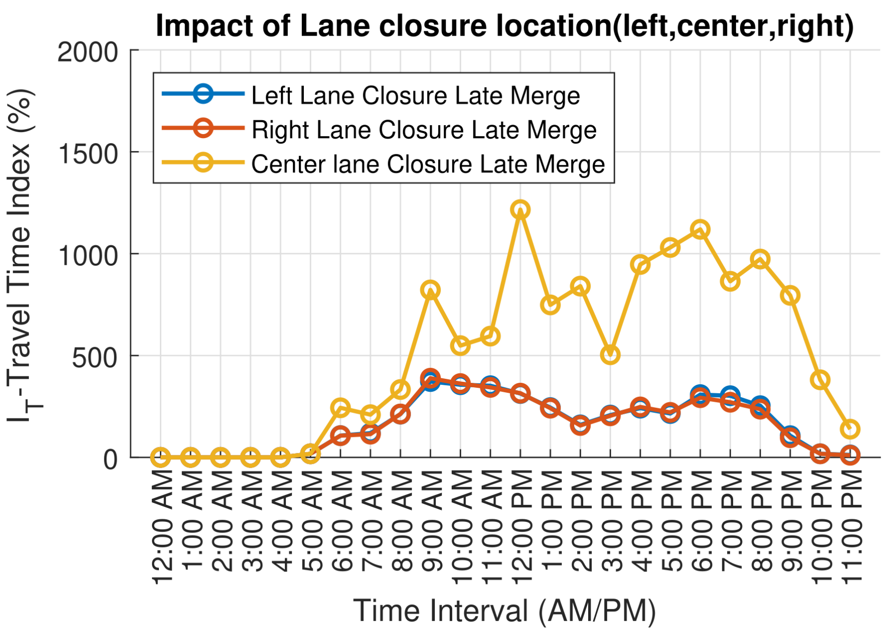

Figure 7. Impact of lane closure location (left, center, right) lane closure; late merge.

Figure 8 and Figure 9 respectively.

As seen in Figure 8, the results for a 10% increase in traffic demand show that the corridor performs similarly to the baseline model and can easily manage the 10% extra traffic demand. However, higher % increases in traffic demand result in significant increases in travel time and make the corridor heavily congested. With 20% added traffic demand, the model can recover from congestion at 9 pm, whereas under a 30% increase in traffic demand, the model cannot fully recover.

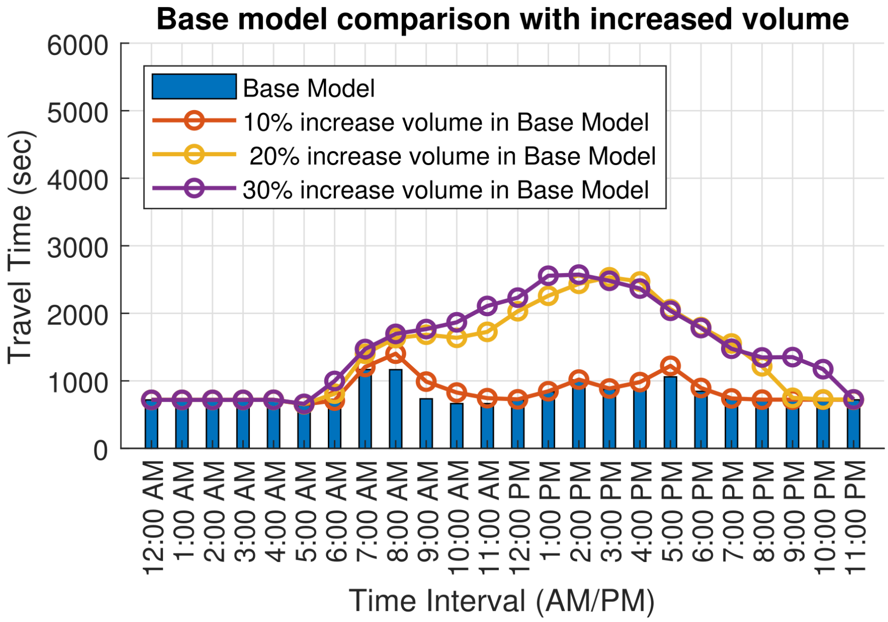

Figure 8. Base model comparison with the increase in traffic volume.

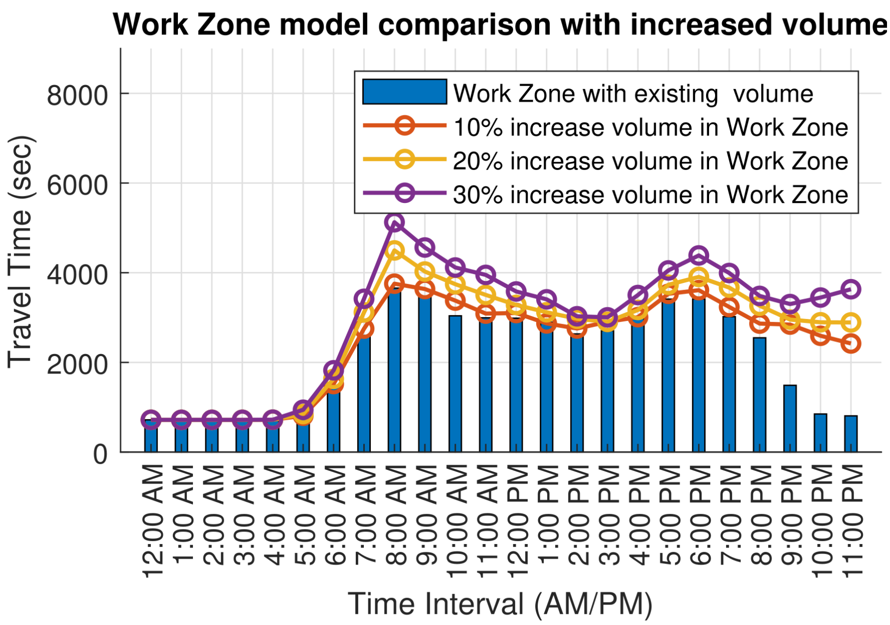

Figure 9. Work zone model (3000 ft; late merge; left lane closure) travel time comparison with increase in traffic volume.

The work zone models were also tested with increasing traffic demand for various combinations of lane closure placement, length, and TTC. Sample results are shown in **Figure 9** for a work zone scenario with a 3-to-2 left lane closure and work zone length of 3000 ft operating under late merge. As seen from **Figure 9**, a 10% increase in traffic volume in the work zone has no noticeable impact on travel time thus the study corridor performs almost similarly to the work zone with existing volume. However, in the later hours of the day (9:00 pm to 11:00 pm), the work zone with existing traffic volume can recover from the congestion, which is not the case when a 10% increase in traffic demand is implemented. Besides, when the corridor operates under work zone presence scenarios, a 20% and 30% increase in traffic volume results in a drastic increase in travel time, leading to significant congestion that overwhelms the facility.

5.5. Impact of Truck Percentage Variation

An increase of heavy vehicles presence in the bottleneck location is expected to have a negative impact on travel times along the study corridor. To quantify such impacts, a comparison between travel time for the baseline model and that resulting from work zone scenarios with varying percentages of trucks in the traffic stream was performed on the basis of I_T. More specifically, due to the absence of detailed truck volumes, the baseline model assumed a constant 10% truck volume. The impact of variations of truck percentages (from 10% to 25% in steps of 5%) on corridor travel time for the base model are summarized in **Figure 10**. Sample results obtained for a 3000 ft long 3-to-2 work zone with a left lane closure operating under late merge TTC are presented in **Figure 11**.

It can be observed that while an increase of truck percentage to 15% is manageable, further increases have a significant negative impact on performance

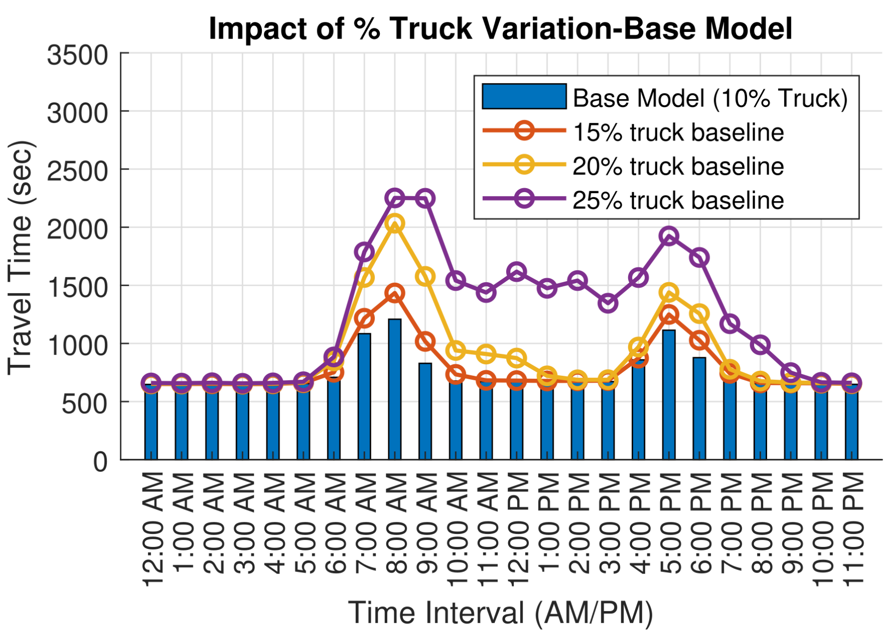

Figure 10. Base model travel time comparison with increase in the truck percentage.

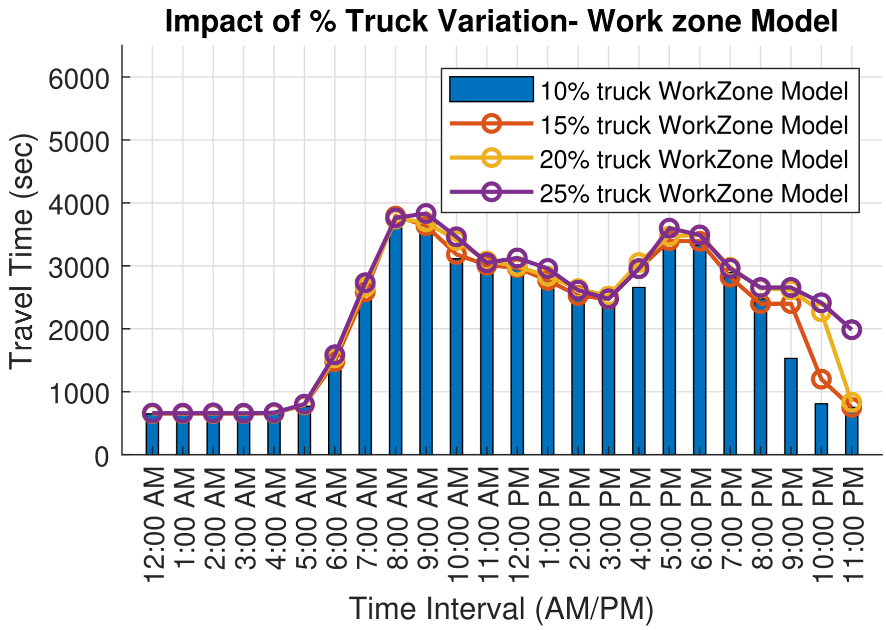

Figure 11. Work zone model (3000 ft; late merge; left lane closure) travel time comparison with increase in the truck percentage.

during peak hours with travel times doubling when the percentage of trucks reaches 25%. Inspection of **Figure 11** indicates that due to the deterioration of conditions and system brake down in the presence of work zone there is not much difference directly attributed to truck % increase. However, for lower truck percentages, the system is expected to recover somewhat faster, as confirmed by **Figure 10**.

5.6. Statistical Analysis

While visual comparisons of the results provide valuable insights of similarities and differences in performance among options considered, it is also important to find whether the differences found in MOE's have statistical significance. For that purpose, statistical analysis was performed on the basis of a t-test to formalize the comparisons and identify options that yield better outcomes. Statistical analysis provides a systematic mechanism for making quantitative decisions more convincingly.

In our study, comparing the MOE's generated from different models through the use of a t-test provided a way to determine whether the differences are significant or not. A statistically significant difference in results implies that one of the two options tested performs better than the other, thus should be favored. **Table 2** summarizes the findings from one tail t-tests performed in this study for a variety of conditions examined and denotes the P-values obtained from the statistical analysis. A P-value that is less than 0.05 indicates that the difference between the MOE's between the two models is significant at 95% confidence level.

From close inspection of the results summarized in **Table 2** it can be concluded

Table 2. Results from one tail t-test performed for statistical significance analysis.

Comparison between	Time period*	MOEs	P value	Significance
Left Lane Closure (LLC) Early Merge VS Right Lane Closure (RLC) Early Merge	Morning peak	Delay	0.1334	Not significant
(LLC) Early Merge VS (RLC) Early Merge	Evening peak	Delay	0.0407	Significant
(LLC) Late Merge VS (RLC) Late Merge	Morning peak	Delay	0.3516	Not significant
(LLC) Late Merge VS (RLC) Late Merge	Evening peak	Delay	0.2225	Not significant
Work zone with 20% VS 25% Truck	Morning peak	Travel Time	0.0364	Significant
Work zone with 20% VS 25% Truck	Evening peak	Travel Time	0.4760	Not significant
Base Model VS 10% Increased Volume in Base Model	Morning peak	Travel Time	0.0817	Not significant
Base Model VS 10% Increased Volume in Base Model	Evening peak	Travel Time	0.0588	Not significant
Work Zone with 10% VS 20% Increase in Volume	Morning peak	Delay	0.0261	Significant
Work Zone with 10% VS 20% Increase in Volume	Evening peak	Delay	0.0101	Significant

that under the early merge, a right lane closure yields significantly better travel times under the 3-to-2 scenario. During peak hours, travel time in work zones increases significantly when the traffic demand increases from 10% to 20%.

6. Conclusions and Recommendations

6.1. Conclusions

The operational impacts of changes in work zone setups and traffic composition were quantified using measures of effectiveness (MOEs) obtained from PVT VISSIM. The major conclusions and findings from the case study are summarized below.

- Variation of work zone lengths did not result in statistically significant changes in travel time along the corridor. Thus, the work zone length is insignificant.

- The operational performance of the corridor under the left-most and right-most lane closure assumption is pretty similar.
- Center lane closure result in significantly higher travel times compared to right-most and left-most lane closures. Thus, it is recommended that center lane closures be avoided. When they are absolutely needed, provisions should be in place to divert some traffic demand away from the facility.
- With the increase in traffic demand along the corridor, travel time is also increased, as expected. The results show that the study corridor can easily absorb about a 10% increase in traffic demand or an additional 5% of trucks without facing a major effect on existing operational performance. Further increases are not advisable as they lead to a breakdown of traffic operations and persistent congestion, especially in the presence of work zones.

6.2. Study Limitations and Recommendations

While the study provided valuable insights regarding work zone design, placement and operation and associated impacts, some limitations still exist. For example, the baseline model was properly validated first and then modified to create work zone models by introduction of lane drops. However, due to the lack of field data representing the various work zone scenarios considered in this study, the simulation models representing work zone operations were not validated directly. To the extent that this is feasible, it is recommended that future studies seek opportunities to collect field data from work zones and use them to validate simulation models replicating work zone field operations in the office environment. Moreover, several assumptions were made in this study in the absence of real data including heavy vehicle use (10%), grades (0%), and driver behaviors. These assumptions were kept unchanged through all experiments conducted in this study, thus did not have any impact in the results. Still, calibration of assumed values of these parameters using field data is desirable in future studies in order to better reflect local characteristics and conditions. Also, the effect of vehicles avoiding the freeway due to construction activity closure was not taken into account in this study but may be considered in follow up research. Additional work is also recommended to investigate in depth the true effect of the center lane closure on operations as this topic received little attention is the literature and the results from this study are also not convincing.

The case study considered only one 10-mile corridor along I-65 in Birmingham, AL. It would be valuable to analyze and compare results from other freeway corridors with similar characteristics to confirm that the findings are consistent and transferable to other locations.

Also, all the analyses performed in this study were for 3-to-2 lane closure scenarios over 24-hrs. Future studies can evaluate the operational impacts of 3-to-1 lane closures and short-term lane closures. Given that the analysis in this study focused only on typical weekday operations, future studies can also investigate the performance of various lane closure options and traffic control strategies during weekend operations. Last but not least, follow up research can evaluate the impact of the dynamic merge control for various lane closure scenarios both for peak and off-peak and compare findings with those obtained under early merge and late merge traffic control.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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