order to describe driver behavior in response to changes in typical congestion patterns. As more data becomes available from ITS and third-party providers, it is possible to better understand the impact of such assumptions.

This paper is organized as follows: The section on the experimental design used in this research is followed by documentation of the base scenario and proposed ICM strategies. Then results associated with all test scenarios are presented followed by a concluding section presenting the benefits and limitations of using simulation-based DTA models.

EXPERIMENTAL DESIGN

This paper presents an application of simulation-based DTA models for the study of ICM strategies in the Austin, Texas, regional network. We describe the modeling workflow and demonstrate the use of data to validate model results and inform the selection of parameters that define driver behavior. A real vehicle-pedestrian fatal crash on Interstate 35 within Travis County, Texas, that occurred on 7:45 pm November 20, 2017, was chosen for this research. Data from smart-flow work zone trailers, Bluetooth sensors, and Google Traffic was used for validation.

In order to estimate the benefits of ICM strategies under incident conditions, a Base Case model that represents typical traffic conditions in the Austin area between 6 p.m. and 11 p.m. was developed and validated. The Base Case model results were used as a benchmark to comparatively evaluate the traffic impact of an incident under four ICM scenarios, including a no-ICM scenario. Two additional scenarios were designed to explore the value and limitations of DTA for the selected application: Early Closure Information and Best Incident Case.

This study executed two different modeling workflows to evaluate the impact of different strategies. Dynamic User Equilibrium (DUE) approach, an accepted method to represent recurrent traffic conditions (Mahmassani et al 1993), was used in two scenarios:

- **The Base Case Model** captures the traffic conditions on a typical day during the analysis period. Using typical DUE assumptions, this scenario identifies an origin-destination path for each traveler in the network. Typical paths are used in subsequent scenarios to define detours when a link is closed.
- **The Incident Best Case** pictures the best possible network performance when a road link is closed due to an incident. It assumed that all drivers affected by the incident are well-informed about their best alternative routes with minimal additional cost. While model results do not necessarily represent an attainable scenario, they indicate a lower bound of the potential impact of an incident. The base case results can be used to quantify the extent of how efficient an alternative route can be.

Then, simulations were constructed to model the selected traffic incident and ICM strategies. The simulations enable the analysis of non-recurrent events, compared to the results from a DUE model. The method assumes that most drivers follow paths that they would take on typical day and allows for a subset of drivers to use pre-specified detours around locations with atypical traffic conditions, such as a lane closure. The simulations modeled the following scenarios:

- **Incident Base Case and ICM scenarios**: At least one alternative route is provided to drivers directly affected by the incident. The ICM scenarios include strategies such as dynamic message signs (DMS) to inform detour alternatives and adjustments to traffic signal controls.

- **Early Closure Information**: When an incident occurs, drivers may receive pre-trip or en-route information so that they have an option to a) cancel a trip or b) choose a path with little or no overlap with their "typical" path.

For all the modeled scenarios, this study used a simulation-based DTA package (VISTA - VTG Inc.) that enforces roadway capacity, captures the propagation of congestion, and explicitly models traffic control at intersections. The next section describes how diversion around non-recurrent congestion is modeled in VISTA.

Diversion Under Non-Recurrent Congestion

Similar to other simulation-based DTA software tools (e.g., Dynus-T and DynaSMART), VISTA supports the modeling of driver reactions to atypical traffic conditions through the incorporation of dynamic message signs and the definition of appropriate alternate routes. DMS may be placed on any network link and display messages about two or more alternative routes that begin downstream from the DMS location and start and end on common nodes.

Drivers often have a "typical" path (noted by a typical start and end node in simulation). Between these two nodes, there are a "typical" route and an alternative route. Drivers are allowed to switch between routes at run time. Drivers would take the alternative route only when the alternative exhibits a lower travel time (or cost) than their "typical" route. Modelers may specify a "compliance" value to represent the maximum number of drivers who would consider the alternative route.

The proposed approach is featured by not enforcing a detour if it is not justified by the traffic conditions. Limitations to this approach include:

- The need for pre-specified detour alternatives is the same to most drivers.
- A detour is a sub-path that has a start and end node in a trip's original route for the typical path.
- It does not accommodate the modeling of detours motivated by pre-trip or early en-route information.

SCENARIO DESCRIPTION

Base Case Model

This study developed and validated a Base Case model that represents typical traffic conditions in the Austin area between 6 p.m. and 11 p.m. The model uses travel demand inputs as provided by the Texas A&M Transportation Institute (TTI) from a calibrated Dynus-T DTA model in the 2015 Capital Area Metropolitan Planning Organization's (CAMPO) traffic network (Shelton et al. 2009).

The 2015 Austin regional travel model data were supplied by the CAMPO in TransCAD format. The model covers the entire CAMPO region with 1,462 traffic analysis zones (TAZs), 25,508 directional road links, and 12,141 road nodes. The original data were processed to build a DTA model by adjusting the network representation. The adjustments included the modeling of two-way roadways using separate directed links, the use of separate origin and destination centroids to represent TAZs, and the selection of appropriate speed limits and roadway capacity values for the purpose of traffic simulation. The final DTA network includes traffic signals as well as tolled facilities.

Hourly origin-destination (OD) demand was evenly split into fifteen-minute OD matrices that allow the DTA model to identify different assignment strategies for travelers departing at specific assignment intervals.

Incident Base Case Scenario

This study investigated the potential benefits of ICM strategies in the context of a fatal crash that occurred on November 20, 2017, on southbound I-35 near US-183 southbound (see in Figure 1). Incident details were obtained from TxDOT's Lonestar Incident Detail Report. According to the report, a pedestrian with unknown reasons illegally crossed the highway and was hit by a vehicle. The incident began at 7:53 p.m. and ended at 10:43 p.m.—a duration of 170 minutes, causing all southbound lanes closed. To simplify the model, the incident start time in the model was set to 7:45 p.m. and the road link where the crash occurred was fully closed for three hours (180 minutes).

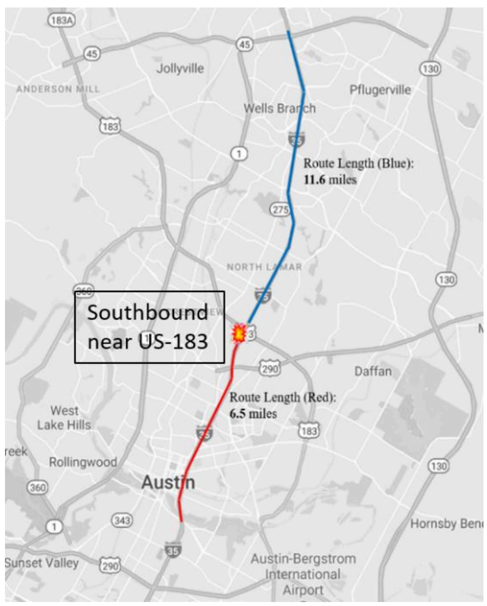


Figure 1. Map of Incident Location and Representation of the Corridors Defined in the Models.

The incident was simulated in VISTA by closing all affected lanes for three hours. Drivers whose typical routes contain the incident link were diverted to the frontage road at the last exit ramp upstream of the incident (Ramp 240) and would return to their original routes immediately when possible downstream (Detour 2 in Figure 2). Drivers originally entering the I-35 South at Ramp 240 would remain on the frontage road and join the corridor downstream from the incident (Detour 1 in Figure 2).

Work Zone Trailer Data Collection

Work Zone trailer data was obtained from TxDOT for validating simulation results. The trailer data obtained include traffic volume for the target area every five minutes. The collected data was prepared by eliminating the outliers and aggregating as needed in the validation step.

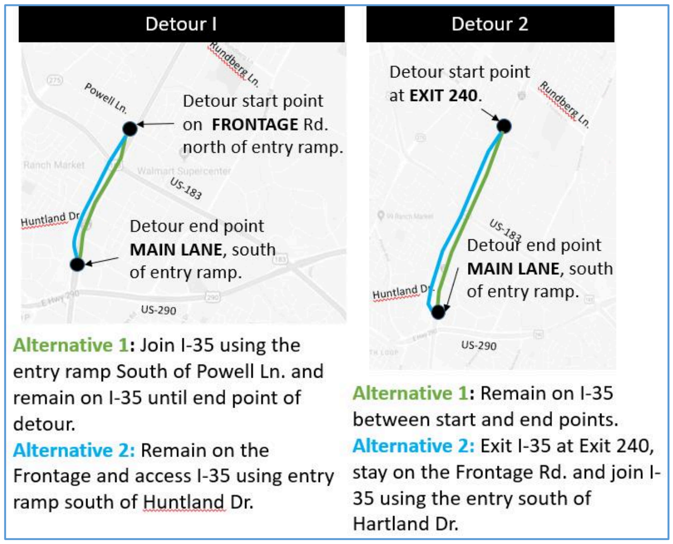


Figure 2. Traffic Detours Considered.

ICM Strategies, Incident Best Case, and Early Closure Information Scenario

This study examined three ICM strategies based on conversations with TxDOT and local stakeholders in Austin area, considering the current capabilities of the available modeling tools. The strategies can be briefly described as follows:

- ICM 1—Additional DMS. This strategy provides the alternative of an early detour to the frontage road by placing an additional DMS on Ramp 241 (Figure 3). The compliance parameter for the second DMS (20 percent) was adjusted based on trial and error.
- ICM 2—Improved Signal Timing. Considering that more vehicles use the frontage road parallel to the incident link, this approach adjusts signals controlling the frontage road traffic to allow southbound vehicles an extra 20 seconds of green time, while green time of other phases were reduced by 20 seconds to maintain the cycle length. Signals adjusted in ICM 2 are listed in Figure 3.
- ICM 3—Additional Detour to Arterial Streets. Cameron Road, identified to be attractive to drivers based on the best-case scenario results and discussions with TxDOT, was used to propose an additional detour option by considering the impact of dynamic message signs (Figure 3).
- Incident Best Case. This scenario does not involve DMS placement because the DUE approach is used to allow drivers to find new shortest paths based on perfect information. The experiment is intended to provide insight on the maximum benefits expected from a perfect ICM strategy that all vehicles can reach their destinations with minimal influence due to the incident.
- Early Closure Information. This scenario removed 35 percent of trips that originally used the closed link from the network and repeated the simulation with the resulting travel demand. The goal of reducing travel demand through the link was characterized through the impacts of DMS information dissemination not specifically modeled in this effort, as well as social media, radio, and other sources of real-time traffic data updates. The selected reduction parameter is based on insights from the Incident Best Case scenario and on the analysis of data from TxDOT ITS devices.

Figure 3. Map of All ICM Strategies.

MODEL RESULTS

An enhanced method of successive averages (Levin et al. 2015) was used to reach a near-equilibrium solution in simulation. The simulation convergence was improved by conducting gap refinement runs that implement an automated search methodology to adjust the assignment in order to reduce the gap. The final true-gap values are in the order of 4.5 percent.

A total of 10 hours of traffic were simulated to allow most loaded vehicles to exit the simulation network. A standard six-second simulation time step was used in simulation.

Model results consist of various performance metrics of the spatio-temporal trajectories of all vehicles in simulation. This study used a customized result-visualization tool and database queries to develop performance metrics. The following sections describe the result analysis including:

- System-level performance metrics for the study area.
- Analysis of system-level and corridor-based users delay costs.
- Validation of Base Case and Incident Base Case results.

System Level Performance

Table 1 presents system-level performance metrics across scenarios for the two vehicle types considered in this study. Total system travel time (TSTT) is the summation of travel times across all vehicles. Origin-destination travel time (ODTT) quantifies the average trip duration in the network.

Table 1. Aggregate System Performance.

Scenarios	Total System Travel Time (hours)	Origin-Destination Travel Time (minutes)
No-incident Base Case	273,789	16
Incident Base Case	+9,714 (+4%)	+1 (6%)
Incident ICM 1	+5,773 (+2%)	+0%
Incident ICM 2	+4,119 (+2%)	+0%
Incident ICM 3	+3,642 (+1%)	+0%
Incident Best Case	+0%	+0%
Note: Total travel demand used in the simulation includes 1,027,876 passenger cars and 78,727 trucks.		

At the aggregate level, the change of TSTT across scenarios offers a way to understand the benefits of different ICM strategies. When ICM strategies are in place, the TSTT decreases approximately 2–3 percent when compared to the Incident Base Case. Because the regional network is large, including the five counties of the Austin region, aggregate metrics do not necessarily reflect the maximum impact of an incident and/or ICM strategy.

ICM 3 appears to provide the greatest benefit in terms of travel delay (only 1% increase in the travel time from the No-incident Base Case). The benefit could be even greater if more vehicles follow the detour information to avoid the closure.

Figure 4 shows the corridor travel time of each pre-determined travel route (as per Figure 3) across different scenarios. As expected, the downstream traffic (relative to the incident) is not significantly affected by the road closure. The corresponding frontage road segment experiences delays around 5 to 7 minutes. The ICM 2 leads to lower delays on this corridor as it extends green times to accommodate additional traffic volumes diverted from the upstream of the incident. Similarly, ICM 3 results in further reduced delays likely as a result of the diversion of some traffic to the alternative routes. The main lane travel times upstream from the closure are close to 2 hours in the Incident Base Case, which represents more than 100 minutes of delay. The results show that ICM strategies can dramatically decrease the delay. In the ICM 3 scenario, which includes all detours and signal changes favoring southbound traveling vehicles, the corridor travel time is reduced to approximately 20 minutes (relative to the Incident Based Case), with only 10 minutes of delay.

In addition, the benefit of extending green times on the alternative route can be examined comparing the simulation results from ICM 1 and ICM 2 scenario. Although the ICM 1 and ICM 2 exhibit similar maximum queue length, the ICM 2 leads to further decreased delays on the main lanes and a shorter congested period. Extending green times on the alternative route is helpful in reducing delays for diverted traffic.

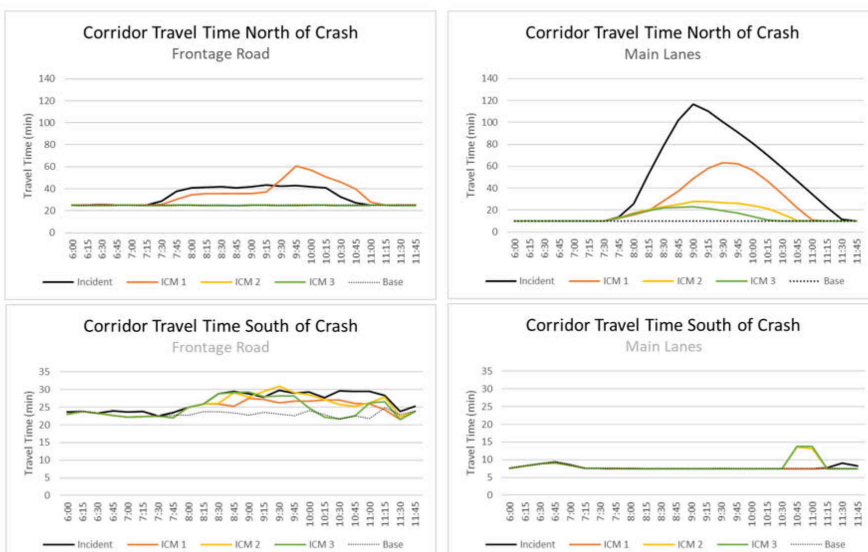


Figure 4. Corridor Travel Time across Scenarios.

Analysis of User Delay Costs

User delay costs were calculated based on the estimated delay time and value-of-time in Texas ($29.05/h and $60/h based on TTI latest estimates for passenger cars and trucks, respectively).

Results in Figure 5 show that the maximum system-wide costs of the incident could be approximately $280,000 due to the incident if no ICM strategy. The costs could be higher if commercial vehicles are considered. The ICM strategies proposed in the model, particularly in ICM 3, show that delay costs could be reduced to approximately $100,000.

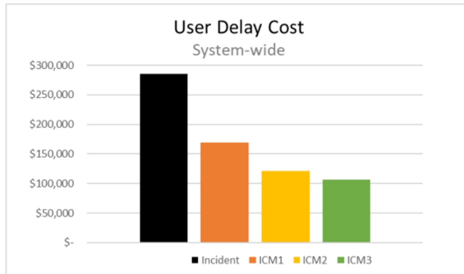


Figure 5. System-wide User Delay Costs

Figure 7 distinguishes between the delay cost experienced by two groups of travelers:

- Group 1 travelers: Their typical routes include the incident link, and their travel time can be directly affected by the incident (see in Figure 6(a));
- Group 2 travelers: Their typical routes do not include incidents but their travel time could be indirectly influenced by the Group 1 travelers who are diverted from the incident link (see in Figure 6(b)).

As expected, Group 1 travelers gain more benefits from ICM strategies than Group 2 travelers. In the re-equilibration scenario (Early Closure Information) drivers that are not originally assigned to the closed link are observed to experience travel-time benefits, probably as a result of improved traffic conditions downstream of a bottleneck.

Figure 6. User-specific Delay Costs.

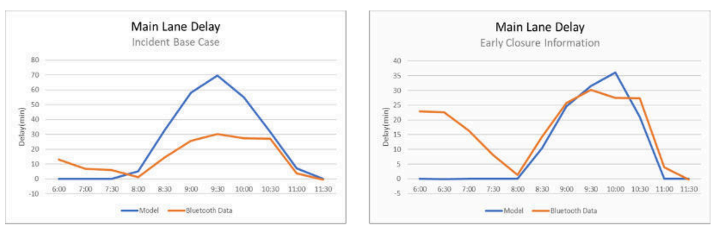
Incident Base Case validation and Early Closure Information results

This study used travel time data along the defined routes to validate the Base Incident Case delay predictions. Validation data were obtained from Lonestar Incident Reports. The goal of the validation effort was to understand the validity of the assumptions regarding the behavior of drivers under non-recurrent congestion. Figure 7(a) compares the delays observed on the day of the incident to those predicted by the model. Observed delays were computed as the difference in reported travel times on the day of the incident and on a "typical" day (11/20/2017). Model delays reflect the difference in corridor travel time between the Incident Base Case and the Base Case. Both metrics are computed using estimates produced every half-hour. The results suggest that the

Incident Base Case over-estimates the observed delay, which was on the order of 30 minutes. While the data used for validation may under-represent the actual incident impacts by considering a longer corridor, the observed difference is still significant. One possible explanation is that real drivers use pre-trip and en-route information and their subjective assessment of downstream traffic conditions to divert from their original paths before they reach the exit ramp.

This study conducted an additional experiment (Early Closure Information Scenario) to understand the potential of improving model results by better capturing driver behavior. This scenario involved removing a fixed percent of trips that originally used the closed link from the network and repeating the simulation with the resulting travel demand. Based on insights from the Incident Best Case scenario, 35 percent of the trips that would use the incident link on a typical day were removed from the network. The resulting delays (see in Figure 7(b)) are notably consistent with field observations.

The results from the Early Closure Information scenario highlight the importance of conducting additional work to understand how travelers would react to pre-trip road closure information due to traffic incidents. Important questions include who are likely to remain in their original route until the last chance to change their route to get around the incident section, where travelers are likely to change their route except the last possible intersection or interchange before the incident section, how travelers would comply to the detour guidance information, and how to improve the effectiveness of detour information dissemination.



(a) (b)

Figure 7. Main Lane Delay for Incident Base Case Scenario and Early Closure Information Scenario.

Base Case Model validation

This study used two types of field data to validate the No-incident Base Case during the time period, including traffic volume data and travel time data.

Table 2 shows the volume-based validation results. Traffic volumes at selected locations were gathered from the smart work-zone trailer data. The selected ITS devices collect 1-minute speeds and travel times at selected locations along I-35. The Mean Absolute Percentage Error (MAPE) is used to measure the difference between model results (F_i) and observed traffic volumes (A_i), listed below.

$$MAPE = \frac{1}{n}\sum_{i=1}^{n} \left| \frac{A_i - F_i}{A_i} \right|$$

Overall, the model results seem to be reasonable given that the MAPE is located within the range s from 20 to 50. . The model appears to underestimate traffic volumes and the reasons might be related to the planning horizon used to obtain the pre-calibration OD matrix. It is not expected that the underestimated traffic volumes would substantially change the results regarding the effectiveness of ICM strategies, as those results are relative differences between simulation scenarios.

Table 2. Traffic Volume Validation Using Work-Zone Trailer Data.

Roadway	Dir.	Location	RMSE* 7pm-12am
US 183	WB	West of IH35	23%
I-35	SB	North of Rundberg Ln.	22%
I-35	SB	North of US 183	24%
I-35	SB	South of US 183	35%
I-35	SB	North of 51st St.	16%
I-35	SB	North of US 290	18%
I-35	SB	North of Airport Blvd.	19%

In addition, researchers selected a section of southbound I-35 to validate the analysis of travel times. This is a section from McNeil Road in Round Rock, Texas, to Riverside Drive south of downtown Austin and it is divided into two sub-segments based on the incident location according to the VISTA simulations. Data were collected separately for the main lanes and the frontage road. In terms of the observed travel times on a typical day (without incident), this study extracted the travel time information from Google Maps. Table 3 shows the comparison of model results and Google Maps travel times, implying an acceptable level of the model performance.

Table 3. Travel Time Validation Using Work-Zone Trailer Data.

		Travel Times (minutes)	
Travel Time Route	Length (miles)	No-incident Base Case model results (6 p.m.-9 p.m.)	Google Maps Typical times @ 7:30 pm
North of Crash Main Lane	11.6	10.7	10
North of Crash Frontage	11.7	25.1	18-35
South of Crash Main Lane	6.5	7.5	9-16
South of Crash Frontage	6.7	23.14	16-40

CONCLUSIONS

This study constructed a series of simulation-based DTA models to capture the influence of severe traffic incidents on traffic during lane closures, and to evaluate the potential benefits of ICM strategies on downsizing the influence. The model results indicate that providing early detour options to affected travelers and adjusting traffic control on detour routes can effectively mitigate the travel time delays among affected travelers. Additional findings from models include:

- At the system level, the implementation of ICM strategies may significantly mitigate the impact of unplanned lane closures by reducing their effects on total system travel time by 2-3 percent.
- Closure-related delays are more substantial for drivers traveling from/to specific origins/destinations, which suggests that targeted information and custom detours may be effective in reducing system-level impacts.
- As expected, the benefits of ICM strategies increase as more detour options are provided upstream from the closure, for given compliance assumptions.
- Adjusting signal timing plans on the facilities that receive the diverted traffic is beneficial for both corridor and system-level performance.
- Considering traffic detours that involve arterial facilities may mitigate delays on the main lanes and frontage roads and does not necessarily worsen system-level performance.

One of the limitations of this research is that the validation results of traffic volume and travel time are off compared to the observed values. The purpose of this research is to illustrate that DTA simulation-based models could be implemented to evaluate the ICM strategies. The future work could be extended to adjust the traffic demand used in the model to make the base scenario more consistent with the actual situations.

REFERENCES

Chu, L., Liu, H. X., and Recker, W. (2004). Using microscopic simulation to evaluate potential intelligent transportation system strategies under nonrecurrent congestion. *Transportation Research Record*, 1886(1), 76-84.

Florian, M., Mahut, M., and Tremblay, N. (2008). Application of a simulation-based dynamic traffic assignment model. *European journal of operational research*, 189(3), 1381-1392.

Guin, A., Porter, C., Smith, B., and Holmes, C. (2007). Benefits analysis for incident management program integrated with intelligent transportation systems operations: Case study. *Transportation Research Record*, 2000(1), 78-87.

Levin, M. W., Pool, M., Owens, T., Juri, N. R., and Waller, S. T. (2015). Improving the convergence of simulation-based dynamic traffic assignment methodologies. *Networks and Spatial Economics*, 15(3), 655-676.

Lindley, J. A. (1986). Quantification of urban freeway congestion and analysis of remedial measures. Final report (No. FHWA/RD-87/052).

Lindley, J. A. (1987). Urban freeway congestion: quantification of the problem and effectiveness of potential solutions. *ITE journal*, 57(1), 27-32.

Liu, Y., Li, P., Wehner, K., and Yu, J. (2013). A generalized integrated corridor diversion control model for freeway incident management. *Computer-Aided Civil and Infrastructure Engineering*, 28(8), 604-620.

Mahmassani, H. S., and Peeta, S. (1993). *Network performance under system optimal and user equilibrium dynamic assignments: implications for ATIS*. Transportation Research Board.

Mahmassani, H. S. (2001). Dynamic network traffic assignment and simulation methodology for advanced system management applications. *Networks and spatial economics*, 1(3-4), 267-292.