LARGE-SCALE INCIDENT-INDUCED CONGESTION: EN-ROUTE DIVERSIONS OF COMMERCIAL AND NON-COMMERCIAL TRAFFIC UNDER CONNECTED AND AUTOMATED VEHICLES

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ABSTRACT

When large-scale incidents occur on freeways, en-route traffic diversion is one effective strategy to reduce the impact of incident-induced congestion. In corridors with substantial commercial traffic, e.g., trucks, route diversion is complicated compared with non-commercial vehicular traffic, due to tough vehicle maneuvers along alternate routes, and higher safety risk. To address the issue of commercial vehicle diversions to alternate routes in response to large-scale incidents, this paper establishes a microscopic simulation methodology to analyze the impacts of various technologies on en-route diversion under large-scale traffic incidents in real-life corridors for single-unit and multi-unit trucks and passenger vehicles. Results show, in addition to incident duration and lane blockage, important factors as CAV, incident information availability, number of intersections, AADT, impact en-route truck diversions and hence the resulting delays. In future traffic operations practice, customizing incident information to truck and passenger vehicles separately is recommended.

1   INTRODUCTION

Under incident-induced congestion along the freeways, upstream travelers may react in different ways in response to this situation. They can either stay in the traffic queue and wait for the incident to be cleared or divert to alternative routes. In corridors with substantial commercial trucks, en-route diversion is far complicated compared to non-commercial vehicular traffic considering vehicle maneuvering, travel time, etc. Commercial trucks need special traffic operations in such situations, due to their weight, traffic impact, roadway erosion, safety, energy, etc. Therefore, to make good decisions in terms of detouring, traffic information (e.g., predicted incident duration, lane blockage, current freeway and alternate route travel time) becomes critical. En-route traffic diversion is typically deployed by Traffic Management Centers (TMC) besides incident site clearance under large-scale incident-induced congestion situation.

However, the benefits of applying the en-route diversion strategies for commercial trucks are not well understood, especially under Connected and Automated Vehicle (CAV) environment. Therefore, this paper intends to study the benefits of applying truck en-route traffic diversions under large-scale incident-induced congestion scenarios with CAV technology. These scenarios are based on a realistic Interstate freeway (I-40) corridor in Knoxville area, Tennessee (TN). To be specific, this study first constructs a microscopic simulation model to analyze en-route diversion strategies along I-40 corridors for trucks and passenger vehicles under different incident scenarios. Secondly, this paper estimates benefits obtained by using different traffic information penetration ratio, value of travel time (VOT), incident duration, CAV, etc. Suggestions based on the simulation results are provided at the end of this paper and recommendations are also valuable for TN Department of Transportations (TDOT) traffic operations.

2   LITERATURE REVIEW

A technical report from Federal Highway Administration (FHWA) defines an alternative route as a route begins from one point on the primary route and terminates at another point on the primary route (Dunn Engineering Associates 2006). So, the alternative route for a freeway starts from an exit to alternative routes and then returns to the freeway on another ramp. However, most of the alternative routes cannot be used by trucks due to their weight, height, width, and turning radius. In the state of TN, alternative routes for trucks along major freeway and highways in metropolitan areas are defined such that trucks can take certain alternative routes upon a large-scale incident-induced freeway congestion (TDOT 2012). Unreliable travel time is identified as the most problematic outcome of incident-related congestion, which is a significant factor for long-haul truck drivers in making route choices as they navigate through the U.S. highway network (Golob and Regan 2001; Knorring et al. 2005). Factors impacting the en-route diversion decisions include incident duration, number of blocked lanes, flow rate on routes, number of intersections on detour route, etc. Generally, under long-duration incident scenarios, higher diversion rates can be observed (Liu et al. 2012; Liu et al. 2011; Yin et al. 2012). However, detour operations can also cause problems on alternative routes. Even though system delay in vehicle-hours is reduced for the freeway, delay on detour routes can increase by 64%, causing unexpected congestion in detour routes (Cragg and Demetsky 1995). This phenomena is called Braess's paradox (Tumer and Wolpert 2000), which is caused by the distinguished difference between travelers' perceived travel time and the system optimum minimized travel time pursued by traffic management team, which is very common in traffic operations (Sheffi 1985). In terms of traffic information systems, dynamic route guidance systems (e.g., Google Maps, GPS, 511) are found to be effective in travel time savings for passenger vehicles as well as public buses and trucks, especially during morning or afternoon peak hours upon non-recurrent incidents (Ng et al. 2006; Pan and Khattak 2008; Sundaram et al. 2011). However, route choice behaviors during a trip can be greatly diverse for each individual in terms of route diversions (Papinski et al. 2009). Therefore, the uncertainties within the system make the en-route diversion analysis complicated.

When estimating the benefits of deploying en-route diversions, VOT should be considered. Due to the heterogeneity and uncertainty of truck industry categories, estimating VOT for each individual truck on the road is complicated and unrealistic. Commercial trucks are studied to have much higher VOT than passenger vehicles, so incorporating VOT in the analysis for truck en-route diversions is necessary (Belenky 2011; Pan and Khattak 2008). However, seldom studies have focused on truck en-route diversions upon a non-recurrent large-scale incident scenario along the freeways under CAV. A large-scale incident usually lasts longer than 2 hours and blocks lanes on freeways, sometimes even all the lanes are blocked (Li et al. 2017). Therefore, incident characteristics, as well as alternative route characteristics (e.g., number of lanes, AADT, number of intersections, etc.), may eventually impact the operational decisions made by TMC managers. Figure 1 conceptually shows a typical TMC detouring operation strategy activated upon the traffic incidents.

To sum up, by studying the en-route diversion strategies for trucks under large-scale incident scenarios, this research aims to fill in the research gap by using simulation models to evaluate the benefits by diverting the truck traffic as well as the passenger vehicles from freeways to arterials (namely, from I-40 to Kinston Pike in Knoxville, Tennessee). This study is timely and original in the sense that truck flow grows significantly in the state of Tennessee, and estimating the benefits in diverting the commercial trucks to alternate route upon a large-scale incident is very important in freight traffic management.

3   METHODOLOGY

3.1   Network and Experimental Design

This study uses TransModeler to run the simulation analysis. TransModeler is a powerful and versatile traffic simulation package applicable to a wide array of traffic planning and modeling tasks (Corporation 2017). It can simulate all kinds of road networks, from freeways to downtown areas, to illustrate and
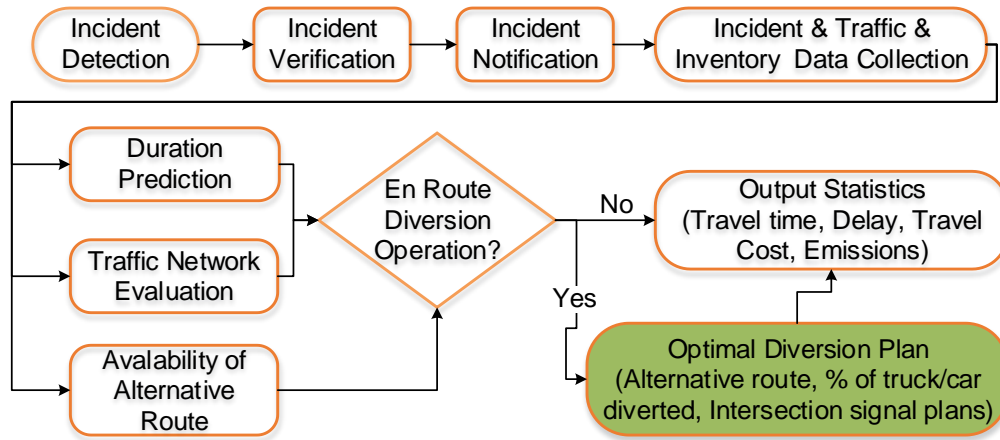
Figure 1: En-route traffic diversion operations system flowchart under the incident situation.

evaluate traffic flow dynamics, traffic signal and ITS operations, and overall network performance. As for drivers' dynamic route choices, they are modeled based upon historical or simulated time dependent travel times, and trips based on Origination-Destination (OD) tables. Therefore, to run the simulation analysis, the OD matrix should be calculated as input into simulation models. To realistically reflect the real-world operational characteristics for the study network, Enhanced Tennessee Roadway Information Management System (E-TRIMS), a TDOT maintained roadway information system is used to obtain traffic data such as Annual average daily traffic (AADT), and other key variables which are grouped as follows (see Table 1 for more details and 8 diversion locations along I-40 Eastbound exits: 369, 373, 374, 376, 378, 379, 380, 383):

- Freeway-related variables: number of lanes on freeway mainline, AADT, percentage of passenger vehicles / single-unit (SU) trucks / multi-unit (MU) trucks;
- Incident-related variables: number of lanes blocked, block duration, travel speed on unblocked lanes, total length of the block area; and
- Alternative route-related variables: AADT on two collector roads connecting freeway and arterial road, and on the arterial road such as Kingston Pike in this study. Number of lanes and intersections, and signal timing plans on these roads.

To investigate various outcomes from simulation models, a conceptual study network as well as a OD estimation graph are introduced for illustration in Figure 2. The diverted traffic includes both passenger vehicles and trucks (SU – Single-Unit trucks, and MU – Multi-Unit trucks). Traffic information is very important in making en-route decisions as mentioned by Sundaram et al. (2011), and Pan and Khattak (2008). If drivers are not informed of updated travel time for incidents happening on the freeway, the potential to divert will be low. So, travel time information penetration ratio (from 0% to 100%) makes a difference in en-route traffic diversions, as well as benefit estimations in simulation analysis. Variations in incident characteristics, VOT of trucks / passenger vehicles, as well as other variables are listed in Table 1.

3.2   Origination-Destination Estimation

In estimating the OD matrix for simulation analysis, 8 simplified nodes in a simplified conceptual network are setup (see Figure 2). Trip productions and attractions (PAs) from Table 1 are used for generating OD matrix. Other data from E-TRIMS are also utilized (e.g., directional distributions of AADT, peak hour traffic direction). The data are error checked and validated, and finally used for

calculating ODs. For example, for location 1, peak hour directional distribution of AADT on freeway is 60% (east direction), so traffic productions for node 1 is 105,970 * 0.6 = 63,582, and attractions is 105,970 * 0.4 = 42,388. Similar operations are done for location 1 to 8. Then these PAs are converted to ODs in TransCAD by applying the internal gravity models. For more details on the conversion, interested readers can refer to (Anas 1983).

Table 1: Key variables in the experimental design for the en-route diversion strategy & initial configurations for eight diversion locations.

Variables	Description	Range of Values
Fr_Ln	Number of main lanes each direction on freeway	3, 4, 5
Fr_AADT	AADT on freeway	105,970, 119,300, 136,250, 179,910, 188,060, 196,210, 196,710
Fr_PerPC	Percentage of passenger vehicles on freeway	70%, 72%, 74%, 76%, 77%, 78%, 80%, 81%, 83%, 84%, 87%, 88%, 89%
Fr_PerSU	Percentage of single-unit trucks on freeway	2%, 3%, 4%, 5%, 6%
Fr_PerMU	Percentage of multi-unit trucks on freeway	8%, 9%, 10%, 11%, 12%, 14%, 15%, 16%, 17%, 18%, 21%, 25%, 27%
Inc_Ln	Number of lanes blocked during incident	3, 4, 5
Inc_BlcDur	Incident blockage duration	$\geq$ 2 hours
Inc_Speed	Travel speed on available travel lane on freeway	10 mph, 15mph
Inc_length	Total length of the blockage during incident	200, 300, 400, 500, 600
Alt_Col1AADT	AADT on collector road 1 from freeway to arterial	10,740, 27,840, 41,820, 63,990, 19,500, 11,420, 19,450, 27,284
Alt_Col2AADT	AADT on collector road 2 from arterial to freeway	27,840, 41,820, 63,990, 19,500, 11,420, 12,550, 14,360, 77,420
Alt_AADT	AADT on alternative arterial	22,570, 29,340, 28,760, 31,090, 19,170, 24749
Alt_Col1_Ln	Number of lanes each direction on collector road 1 from freeway to arterial	1, 2, 3, 4
Alt_Col2_Ln	Number of lanes each direction on collector road 2 from arterial to freeway	1, 2, 3, 4
Alt_Ln	Number of lanes each direction on alternative arterial	2, 3, 4, 5
Alt_Int	Number of signalized intersections on alternative route	2, 3, 4, 5

No	Fr_Ln	Fr_AADT	Fr_PerPC	Fr_PerSU	Fr_PerMU	Alt_Col1AADT	Alt_Col2AADT	Alt_AADT	Alt_Col1_Ln	Alt_Col2_Ln	Alt_Ln	Alt_Int
1	3	105,970	78%	4%	18%	10,740	27,840	22,570	1	2	2	11
2	3	119,300	81%	3%	16%	27,840	41,820	29,340	2	2	2	12
3	4	136,250	83%	3%	14%	41,820	63,990	29,340	2	2	2	7
4	5	179,910	87%	2%	11%	63,990	19,500	28,760	2	3	2	11
5	5	188,060	88%	2%	10%	19,500	11,420	31,090	3	2	2	11
6	4	196,210	88%	2%	10%	11,420	12,550	31,090	2	2	3	9
7	5	196,710	81%	3%	16%	19,450	14,360	31,090	2	2	2	10
8	4	196,410	81%	3%	16%	27,284	77,420	21,960	2	3	2	15

3.3   Traveler Information and VOT

In evaluating the impact of traveler information on en-route diversion strategies, information penetration ratio is set up to vary from 0% to 100%. For each group of drivers from the vehicle fleet passenger cars - PC, SU, or MU, they either receive updated travel time information or not in TramsModeler. For those who do not receive updated travel time information, they remain in the current traffic in TransModeler simulation models; otherwise, they can take the designated alternative route based on the threshold value (5%) of the travel time difference between freeway and alternative route.
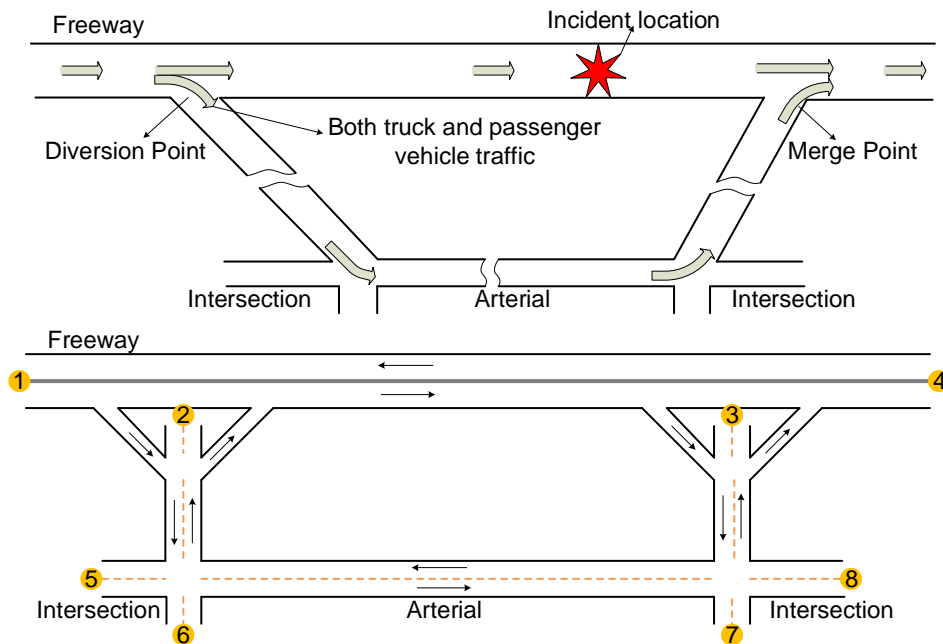
Figure 2: En-route diversion scheme along the freeway & ODs for the study network.

3.4 En-Route Choice Model

Stochastic shortest path method based on path costs is adopted in this study. Compared to deterministic shortest path method, it takes account the variations in each individual drivers' perception and behavior on pre- and en-route choices. Thus, path costs are randomized and there could be many shortest paths between a given O-D pair. TransModeler is a path-based simulation model (Caliper 2014), so each vehicle has an assigned path before departing its origin and entering the network. Simulated vehicles will consider en-route alternative paths if delay experienced on a link far exceeds expected delay which is obtained though dynamic traffic assignment using stochastic user equilibrium method computed by the method of successive averages (MSA) in TransModeler. The threshold for link delay to be considered excessive is determined by each drivers' route choice parameters (e.g., choice set threshold, update delay threshold, reroute threshold). These parameters often vary among the driving population, and they eventually determine drivers' decisions on the alternative paths. Some of the key en-route choice parameter are presented as:

- Informed – access to updated travel time information. Drivers make all en-route choice decisions solely based on historical travel time if no informed.
- Update delay threshold – the percent difference between experienced travel time on a link relative to expected or historical travel time. Drivers may or may not take alternative paths if threshold is exceeded. 20% is used in this study as the update delay threshold.
- Reroute threshold – the percentage reduction in travel time relative to the current path required in deciding to switch to the alternative route. 5% is chosen for PC, while for SU/MU, 10% is used since truck drivers' preference will often be freeway instead of other local arterials, especially for long-haul trucks.

4 SIMULATION ANALYSIS RESULTS

Delay statistics is mostly used among various criteria (e.g., travel time, Level of Service, intersections stops, queue length) in evaluating the performance of en-route diversion traffic operations strategy (Dunn

Engineering Associates 2006; Knorring et al. 2005; Liu et al. 2011; Liu et al. 2012; Yin et al. 2012; Ng et al. 2006; Pan and Khattak 2008). Delay reductions can be treated as travel time savings, and delay reductions of trucks and passenger vehicles can also be converted to savings in emissions, fuel, as well as monetary value. The simulation runs start at 00:00:00 and end at 23:59:59, and incidents are assumed to block all other lanes except one lane on the left side of the freeway, and the travel speed is assumed to be 10 mph for this available travel lane. The incident is set up during morning peak hours from 7 to 9 AM for simulation analysis.

4.1   Delay Outcomes

Figure 3 presents the delay statistics for freeway and alternative routes at 8 locations under different traffic information penetration rate. Those 8 locations are located from rural to urban (1 – 8). Figure 3 (Left) shows the delay statistics for the freeway. Compared to normal traffic situation, if an incident occurs on the freeway and 0% of the drivers in the fleet are informed of the updated travel time, the average delay increased about 4.6 to 8.7 times for freeway diversion points at 8 locations. These statistics indicate a driver will spend 20 - 45 minutes to drive through the segment where normally 5 minutes is enough for the travel. Figure 3 (Left) presents delay reductions for the freeway based on the percentage of drivers in each fleet group having access to traffic information. The results show that with more traffic information delivered to drivers, the en-route diversion rate will increase, and the travel delay reduction will be more. Additionally, under CAV environment, the simulation results show that, traffic on the freeway, if taking en-route diversions from the freeway to alternative arterials at rural locations can save more travel time compared to non-CAV vehicles, because these CAV vehicles can quickly react to incidents with real-time traffic information. The preliminary analysis graphs do reveal a monotonic increasing benefit from the average delay reductions for freeway (up to 8% - 10% at 8 locations) and a monotonic average delay increment for an alternative route (up to 10% - 20% at 8 locations, Figure 3 (Right)). This interesting result indicates that with more traffic related information delivered to drivers, they can quickly respond to the incidents, which generally contributes the overall freeway congestion relief and improve their driving experience. Notice in Figure 3 (Left), compared to rural locations (e.g., location 1 & 2), average delay reductions at urban locations are less. It is probably due to that drivers at urban areas prefer to stay on the freeway since the alternative routes might also be congested at morning peak hour. Therefore, considering the number of intersections and a high chance of long intersection delays, drivers, especially truck drivers still consider the freeway as their primary route choice. While in rural areas, fewer intersections are observed, which might not cause much delay in rural areas. This implies that under heavily congested areas (e.g., downtown area), regardless of traffic information, freeway is still the primary route choice due to high congestion in peak hour as well as tough vehicle maneuvers (e.g., lane changing, merging, diverging, turning).
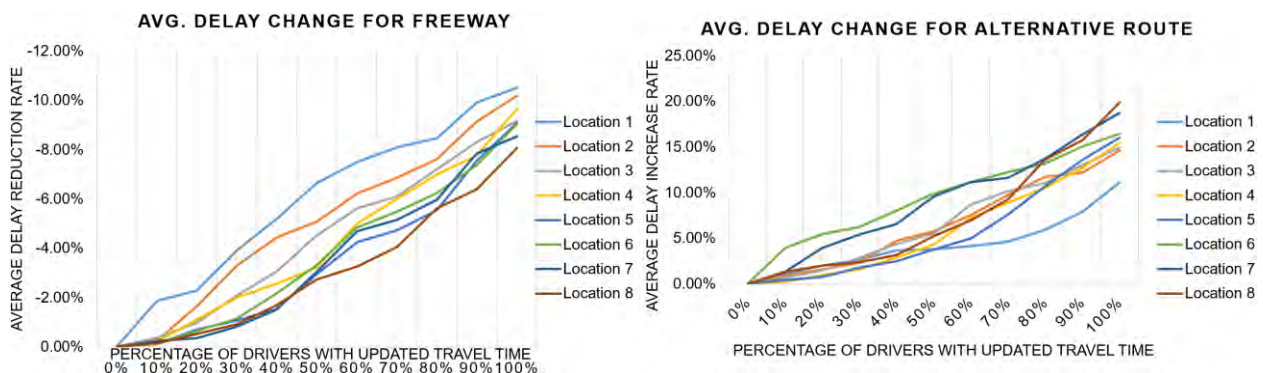

Figure 3: Average delay reductions for freeway at 8 locations (Left); Average delay reductions for alternative route at 8 locations (Right).

4.2 Impact of Value of Travel Time

Assuming 50% of the drivers are updated with traffic information. The impact of VOT on delay reduction is evaluated. Assuming VOT for passenger vehicles is $15 (for illustration purpose only), and VOT for trucks (SU and MU) are set up as 2, 4, 6, 8, 10, and 12 times greater compared to passenger vehicles. If only considering the freeway or detour route separately, then simulation analysis results show that delay reductions for freeway or increments for detour route are not very stable. If both are analyzed together, then delay reduction is much more stable. Higher VOT means higher risk in increasing travel cost if not taking a proper alternative route, so most truck drivers prefer the freeway. If converting travel time savings to dollars using conversion factors in Table 2, results in Figure 4 indicate that comparted to based case ($15 VOT for all vehicles), the overall travel cost savings in percentage declines, even though the total amount of travel cost savings increases. This result implies that when en-route diversion operations are implemented, diverting trucks as well as passenger vehicles is necessary because trucks usually have higher VOT, which contributes to higher total cost savings. However, if the VOT of trucks is way higher, diverting more truck traffic won't increase much in terms of percentage travel time savings.
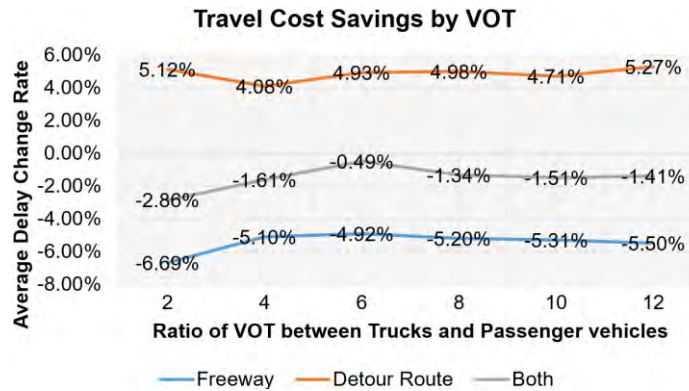

Figure 4: Travel cost savings under different trucks VOTs.

4.3 Impact of Incident Durations

The impact of incident duration is evaluated by studying location 8 in detail. The peak hour direction for I-40 is Eastbound. The alternative diversion route starts from I-40 Exit 383 to Northshore Drive to Kingston Pike to State Route 129, then back to I-40 at 386B. Under normal traffic conditions, travel time on the segment is 4 minutes for 4.3 miles. It is about 13 minutes for 5.6 miles if driving on Kingston Pike with 15 signalized intersections. Figure 5 presents the delay reduction information for the whole study network by assuming 50% of the travelers are updated with traffic information, and incidents start at 7
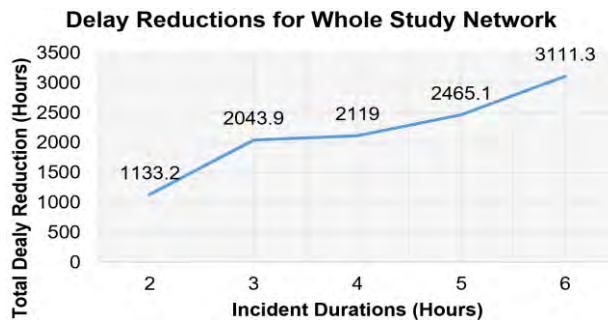

Figure 5: Total delay with updated traffic information under large-scale incident scenarios lasting 2 to 6 hours.

AM and last 2 to 6 hours. Only one lane is assumed to be available for travel at the incident site throughout the whole simulation runs under large-scale incident scenarios lasting 2 to 6 hours. Delay reductions are seen to increase as incident duration lasts longer.

4.4   Benefit Estimation

Benefit estimation can be extended to emission and fuel reductions. Together these savings can be converted to monetary values using the conversion factors in Table 2. Using conversion factors in Table 2, the cost savings are obtained for the incident scenarios lasting from 2 to 6 hours (see Table 3). Results clearly show that with longer incident durations, the benefit of cost savings (in delay, emissions, and fuel) is greater. This result is in accordance with other studies (Chang and Raqib 2013; Liu et al. 2012; Lutsey et al. 2004), and under such large-scale incident scenarios, the magnitude of the cost savings is much larger than non-large incident scenarios.

Table 2: Conversion factors and their sources.

Conversion Name	Value	Source
Delay to HC	13.073 g/h	Chang and Raqib (Chang and Raqib 2013)
Delay to CO	146.831 g/h	Chang and Raqib (Chang and Raqib 2013)
Delay to NO	6.261 g/h	Chang and Raqib (Chang and Raqib 2013)
Delay to CO_2	0.156 gal/h of passenger cars	Ohio Air Quality Development Authority
	0.85 gal/h of trucks	(Lutsey et al. 2004)
CO_2	19.56 lbs/gal of gasoline	Chang and Raqib (Chang and Raqib 2013)
	22.38 lbs/gal of diesel	
Delay Cost	$27.37/h	U.S. Census Bureau 2009
Fuel Cost	$2.264/gal of gasoline (East Coast)	Energy Information Administration
	$2.546 gal of diesel (East Coast)	
HC cost	$6,700/ton ($6.7/kg)	Chang and Raqib (Chang and Raqib 2013)
CO cost	$6,360/ton ($6.36/kg)	Chang and Raqib (Chang and Raqib 2013)
NO cost	$12,875/ton ($12.875/kg)	Chang and Raqib (Chang and Raqib 2013)
CO_2 cost	$23/metric ton ($0.023/kg)	Chang and Raqib (Chang and Raqib 2013)

Table 3: Cost saving for large-scale incident scenarios.

Scenarios (Incident Duration)	Delay Cost Saving	Fuel Cost Saving	HC Cost Saving	CO Cost Saving	NO Cost Saving	CO_2 Cost Saving	Total Cost Savings
2	$31,015	$790.13	$99	$1,058	$91	$71	$33,126
3	$55,941	$1,425	$179	$1,908	$164	$129	$59,748
4	$57,997	$1,477	$185	$1,978	$170	$134	$61,944
5	$67,469	$1,718	$215	$2,302	$198	$156	$72,061
6	$85,156	$2,169	$272	$2,905	$250	$197	$90,952

4.5   Impact of CAV on Network Performance

Vehicle automation has made the progress in improving the surface transportation in terms of mobility and safety. However, seldom has the current existing studies focused their attention on estimating the benefits under the en-route traffic diversion under large-scale traffic incident on the freeways. Thus, the impact analysis of CAVs on network performance in terms of travel delay reductions and average speed, is done to compare the difference between the benefit estimations under various vehicle automation levels and under normal driving conditions with drivers fully controlling the vehicles. Traditionally, the traffic is modeled in the TransModeler using General Motors (GM) car-following models, and its formulation based on TransModeler User's Guide version 5.0 is written as following Equation (1),

$$A_i^\pm[t + \Delta t] = \alpha^\pm \frac{V_i^{\beta^\pm}[t]}{D_{i,i-1}^{\beta^\pm}[t]} (V_{i-1}[t] - V_i[t])^{\theta^\pm} + \varepsilon_i^{CF} \tag{1}$$

Where:

$A_i^\pm[t + \Delta t]$ = Acceleration rate of vehicle i at time + reaction time Δt;
$V_i[t]$ = Speed of subject vehicle i at time t;
$V_{i-1}[t]$ = Speed of front vehicle $i - 1$ at time t;
$D_{i,i-1}[t]$ = Distance between the vehicle i and front vehicle $i - 1$ at time t;
$\alpha^\pm, \beta^\pm, \gamma^\pm, \theta^\pm$ = Model Parameters; + means acceleration, and – means deceleration.
ε_i^{CF} = vehicle-specific error term for the car-following regime.

The acceleration of the subject vehicles happens when its speed is less than the speed of the front vehicle. Otherwise, the subject vehicle will remain constant or decelerate. Lower bound and upper bound of headway are set to limit the vehicles running above the emergency regime and under the free flow regime.

However, under the CAV environment, it is suggested to run the Constant Time Gap car-following model (CTG) to achieve the goal of improving transportation mobility by increasing roadway capacity and travel speed. It follows the concept that drivers seek to maintain a constant, desired following headway with the front vehicle. It is more like a simplified algorithm representing an on-board computer's operating policy. Thus, it can be used to approximate the behaviors of connected vehicles in a cooperative adaptive cruise control environment. Its formulation based on TransModeler User's Guide version 5.0 is written as Equation s(2),

$$\begin{cases} A_i[t] = -\frac{1}{h}(V_i[t] - V_{i-1}[t] + \lambda\delta_i) \\ \delta_i[t] = D_{i,i-1}[t] + hV_i[t] + D_{i,i-1}^{desire} \end{cases} \tag{2}$$

Where:

$A_i[t]$ = Acceleration rate of vehicle i at time t;
h = Desired following time headway (in seconds);
$V_i[t]$ = Speed of subject vehicle i at time t;
$V_{i-1}[t]$ = Speed of front vehicle $i - 1$ at time t;
δ_i = Spacing error for vehicle i requiring correction to achieve the desired headway h;
$D_{i,i-1}[t]$ = Distance between vehicle i and vehicle $i - 1$ at time t;
λ = Model parameter for control purpose.

Various scenarios are created to evaluate the impact of CAV on the network performance based on location 8. First, one of the roadway segments in the simulations models are extracted to compare the simulated traffic flows and realistic traffic flows. By doing so, the simulation model is validated to have represented more realistically about the I-40 and Kingston Pike traffic flow conditions. The segment where traffic entered the freeway network is used. The hourly volume for realistic traffic on this segment is shown to be 4918/hour. Using the Mean Absolute Percentage Error (MAPE) measurement, the averaged value of MAPE for simulated traffic volume and realistic traffic volume is 3.55% based on 70 simulations without any incident. It is an acceptance value, because 5% is usually used for the gap acceptance in TransModeler.

Figure 6 presents the simulation outcomes in terms of total network system delay. A huge change of delay from no automation to level 1 automation. 1.5% - 13% reduction in total delay with incident durations ranging from 675 to 0 minutes. By setting the headways (1.1, 1.0, 0.9, 0.7, 0.6, and 0.5 in seconds) in the 5 automation levels, the scenarios present a monotonically decreasing trends for total

system delay. With less headways between vehicles, the roadway has more capacity, so vehicles spend less travel time in the system. However, after automation level 3, the benefit obtainment is less when compared to lower automation levels. Overall, by deploying the CAV technology into such en-route traffic diversion operation, the traffic network save more travel time. In addition, the impact of truck performance under various automation levels are also investigated, and the results are shown in Figure 7. It indicates that the network performance can be increased by introducing higher performance trucks as well as passenger vehicles. Maximum percentage increase in average speed can be as large as 18.29% when vehicle performance increases by 15% at level 5 automation. Therefore, to sum, both CAV and vehicle performance, especially CAV, play important roles in improving traffic network performance under large-scale incident induced traffic congestion on freeways.
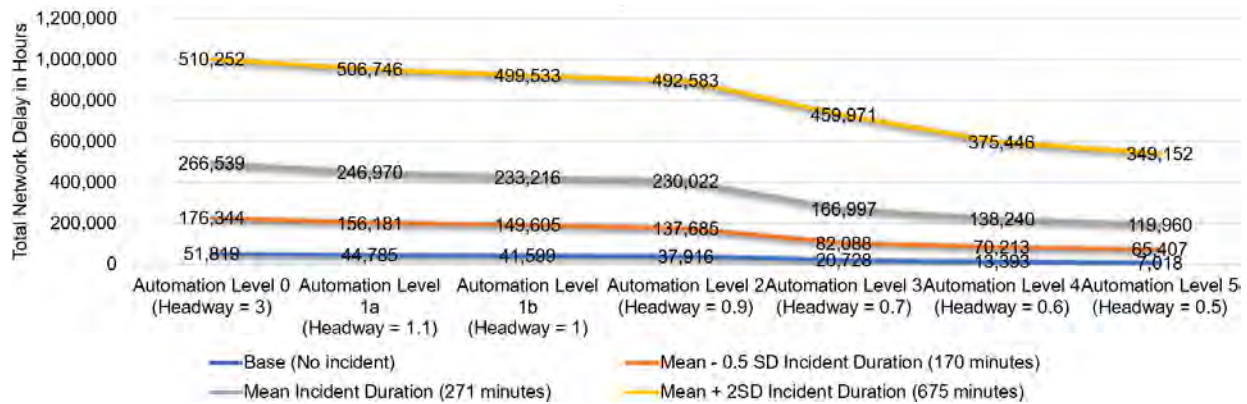

Figure 6: Simulation outcomes in term of system delay with no incidents under 5 levels of automation.
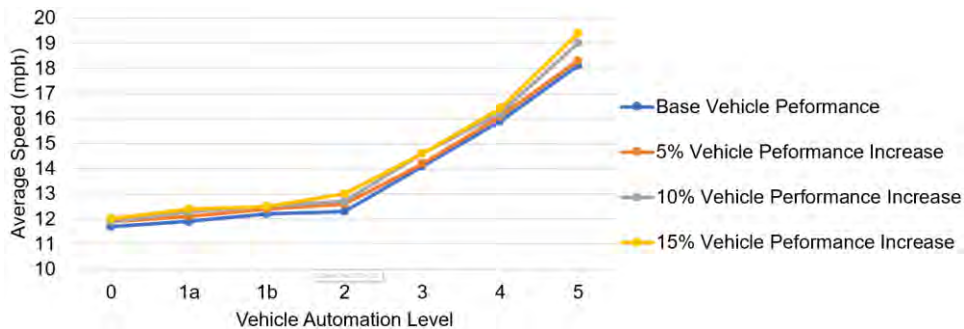

Figure 7: Avg. speed with no incidents based on truck vehicle performance under 5 levels of automation.

5   CONCLUSIONS

En-route traffic diversion operation is one of the traffic calming strategies to deal with traffic incidents. However, seldom research has been done to specifically talking about such diversions under non-recurrent large-scale incident situations for commercial trucking vehicles. Large-scale incidents usually last longer and block more lanes. Therefore, this paper proposed to apply TransModeler simulation models to analyze the delay reductions and cost savings for both trucks and passenger vehicles under CAV. For such a research purpose, the biggest challenge is to calculate a relatively realistic OD matrix for the trips to be allocated within the simulated traffic network. The simulation network models are based on real-life archived data. AADT as well as other data from E-TRIMS are extracted and error checked to achieve such task for the traffic network using TransCAD. Then, it is incorporated into the simulations models to obtain traffic network performance statistics such as system delay, average speed, etc. Some key findings are as follows:

- Benefit in delay reduction for truck as well as passenger vehicles are larger in rural areas than in urban area by implementing the en-route diversion, because AADT and the number of intersections are smaller in rural areas. Applying en-route diversion in these areas will be much beneficial;
- If lots of traffic is diverted to the alternative route, the increase in average delay for alternate route is huge, especially when diverted traffic includes a lot of trucks. Because trucks will spend more time in maneuvering along the arterial. The percentage increase of average delay is even higher for alternative route when compared to average percentage delay reduction for freeway traffic.
- The percentage of travelers accessing the updated travel time has a significant effect on persuading truck drivers as well as passenger vehicle drivers to take the alternative route;
- CAV help save more travel cost when the en-route diversion strategy is implemented under large-scale incidents occurring on the freeways. Also under such scenarios, the longer the incidents, the urgent the implementation of the en-route diversion operations will be.

In the long term, this research will be useful in helping practitioners in evaluating the alternative routes by comparing the benefit estimations. This study highlights the necessity and importance of the customization of en-route diversion information to trucks for traffic management, because truck drivers' primary choice is the freeway and if not well informed and guided, the chance of diverting from the freeway is very low. Such customized information includes the availability of alternate routes for trucks and travel time for trucks on the current freeway and alternate routes. However, due to the Braess Paradox phenomena, truck en-diversion should be controlled to avoid the side effects by limiting the diversion rate. This study is limited to certain number of scenarios and study network. Future research direction will incorporate the signal timing plans to accommodate diverted traffic on alternative routes. Another research direction would be comparing different alternative routes if there are multiple detour routes available to trucks. Truck drivers' en-route diversion behavior is another research question left to be answered, and the surveying work in undergoing. Drivers' en-route diversion behaviors can be used to explain some of the results concluded above, such as why drivers prefer to remain in freeways in urban areas, and this is our next step in truck en-route diversion analysis for truck drivers' behaviors.

ACKNOWLEDGMENTS

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