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Assessing spatial and temporal effects due to a crash on a freeway through traffic simulation

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ABSTRACT

The focus of this paper is to simulate, evaluate and assess spatial and temporal effects in travel time variation and upstream distance or length of upstream links affected due to a crash. Traffic simulations were conducted for different conditions in VISSIM 5.30™ to obtain travel times at various points upstream of the crash location, over time, along a freeway corridor. Travel time variation between fatal crash condition and no crash condition (baseline condition) and between injury crash condition and no crash condition (baseline condition) were computed and compared to evaluate the effect of a crash on a freeway. Results obtained showed that fatal crash on freeways has an effect under low, moderate, and high traffic volume conditions, whereas injury crash has an effect only under moderate and high traffic volume conditions. The travel time variation and upstream distance affected due to a fatal crash on the right-most lane was generally higher than fatal crash on the left-most lane. The trends remained fairly consistent irrespective of the lane on which an injury crash occurred. The upstream distance affected due to a fatal crash varied from 1.5 miles to ~7.5 miles based on traffic volume and lane on which the fatal crash occurred. It varied from ~0.5 miles to 7 miles due to an injury crash and traffic condition. Queue may start dissipating at least 15 min after blocked lanes are re-opened for normal traffic flow depending on the type of crash, traffic volume and lane in which the crash occurred. The results and findings from this research can be applied to emulate dynamic message signs over time and space so as to alert the motorists about the length and duration of congestion depending on the severity of crash and lane on which the crash occurred.

1. Introduction

According to the National Highway Traffic Safety Administration (NHTSA, 2010) of the United States Department of Transportation (USDOT) traffic safety facts, in the year 2010, over 30,000 fatal, 1.5 million injury and 5.5 million total crashes occurred in the United States. In the city of Charlotte, North Carolina, during the same year, over 200 fatal and 22,000 injury crashes were reported. The most common types of collisions on freeways are rear-end, ran-off road and sideswipe collisions. The main factors that contributed to the above collision types are failure to reduce speed when the vehicle in front reduces speed, improper lane change, speeding, and inattentive driving (NHTSA, 2010).

Accommodating and addressing the safety of system users on freeways is vital as associated damages and economic losses are substantial in nature. Crashes occurring in congested conditions are less severe and more likely to be rear-end collisions (Zhou and Sisiopiku, 1997; Chang and Xiang, 2003; Golob et al., 2008). The highest charges on freeway segments are associated with crashes on congested roads during non-peak travel hours (Rothenbeg et al., 2007). Moreover, crashes during uncongested conditions are more severe and may result in relatively high travel time variation.

A majority of safety related research in the past focused on identification of high crash locations and understanding the causes of crashes to improve safety. Likewise, considerable research was done to understand the effect of traffic volume or travel demand on congestion. However, not many focused on understanding the effect of crashes on traffic delay and travel time variation (at and upstream of the crash location) over time and space.

Crashes on freeways not only cause severe damage but also induce vehicle delays along the road network. When a crash occurs

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on a freeway, one or two lanes are blocked (closed) temporarily depending on the type of crash. This results in a temporary reduction in capacity and an increase of vehicle delays on the road network. The total delay would be high when a crash occurs during peak hours (high traffic volume) than when compared to off-peak hours (low traffic volume). However, the variation in travel time (function of difference between travel time under a certain condition and travel time under no crash or off-peak condition) may not follow the same trend. The effect of a crash on travel time variation further depends on the time of occurrence, severity of the crash, the number of vehicles involved in the crash, traffic volume (existing and short-term future), geometric conditions, and the lane on which it occurred.

When a lane or two lanes are blocked due to a crash, queues are formed in the upstream direction. The formation of queue and the effect on traffic delay over time can be examined using travel time variation as a measure. At the same time, the dissipation of queue from the blocked location takes place in the upstream direction. In general, the rate of dissipation of queue is faster than the rate of formation of queue. Therefore, the difference in travel time variation could be higher for the upstream segments some time after the crash (example, 75 min after a fatal crash than 60 min after the fatal crash) due to queue building in the upstream direction but dissipating at a faster rate in the same direction. In case of a severe crash and multiple lanes are blocked for an extended period, the queue and delay could extend further and result in an additional delay under congested conditions.

Therefore, there is a need to examine the effect of a crash on travel time variation on upstream segments over time and space. The spatial and temporal effects need to be evaluated and assessed by traffic condition, crash severity, and the lane (say, right-most or left-most lane) on which the crash has occurred. This research deals with the travel time variation (defined as variation in travel time due to a crash when compared to normal no crash traffic flow condition during the same time interval) and affected upstream distance (based on links with travel time variation) caused due to a fatal or injury crash to study their effect on travel time delay. The objectives of the research are:

1. to simulate and evaluate the effect of a fatal or injury crash, occurring on different lanes, on travel time variation and upstream distance affected along a corridor;
2. to examine the role of traffic volume on upstream distance affected from the blocked section and the duration of travel time variation (congestion); and,
3. to evaluate and assess the queue formation and dissipation pattern over time.

2. Literature review

In the past, research was conducted to calculate travel time variation and travel time delay, as well as to quantify congestion. NCHRP Report 618 discusses the use of cost effective performance measures such as travel time delay, variation and reliability (NCHRP, 2008). The report specifies the minimum number of observations required to obtain a desired confidence level to calculate the mean delay and travel time.

Non-recurring congestion due to crashes and other incidents also play a major role on congestion. Al-Deek et al. (1995) developed a methodology to estimate freeway incident congestion on I-880 in California where extensive loop and incident data are available. Time-space domain was determined for each incident using shockwave analysis, which was used to define the congestion boundaries of an incident and to decide whether the incident should be analyzed as isolated or as a multiple-incident case. Traffic speed and traffic counts upstream and downstream of the incident location were used to compute incident delay on each segment during small time periods, and then used to quantify cumulative incident delay.

Garib et al. (1997) developed two statistical models, one to estimate incident delay and another to predict incident duration. The incident delay models showed that up to 85% of variation in incident delay can be explained using incident duration, the number of lanes affected, the number of vehicles involved, and traffic volume before the incident. The incident duration prediction model showed that 81% of variation in incident duration can be predicted by the number of lanes affected, the number of vehicles involved, truck involvement, time of day, police response time, and weather condition.

Güner et al. (2012) developed a stochastic dynamic programming formulation for dynamic routing of vehicles in non-stationary stochastic networks subject to both recurring and non-recurring congestion. They also proposed alternative models to estimate incident induced delays. Their results looked promising when the algorithms were tested in a simulated network of South-East Michigan freeways using historical data from the MITS Center and Traffic.com. Findings from their study indicate that 50% of all travel time delays are attributable to non-recurring congestion sources such as incidents.

Mansoureh et al. (2011) simulated the post-incident traffic recovery time along a freeway and compared the results with shockwave theory calculations. Their results showed that a higher post-incident recovery time is estimated for traffic to return to pre-incident travel conditions using the simulation method than when using the shockwave theory. They also showed that the recovery time increases proportionally as traffic intensity builds.

Most of the research on non-recurring congestion was conducted using the data collected by agencies. A few authors such as Pulugurtha et al. (2002); Martin et al. (2011) used traffic simulation software to analyze the effect of incidents on transportation system performance in the past. Pulugurtha et al. (2002) explored the features available in CORSIM and VISSIM traffic simulation software to simulate and analyze the effect of incidents. They neither calibrated the model nor focused on travel time variation or upstream distance affected due to a crash. Martin et al. (2011) worked on an analysis of freeway incidents on the Salt Lake Valley freeway network. Different types of incidents were analyzed using VISSIM simulation software. Their analysis focused on incident induced freeway delays and also looked at other parameters such as vehicle throughput, travel times and network-wide delays.

Researchers have also attempted to integrate recurring and non-recurring congestion components to quantify congestion in the past. Pulugurtha and Pasupuleti (2010) developed a methodology to estimate travel time and its variations, travel delay index due to crashes and their severity, congestion score, and reliability of each link in the network for the city of Charlotte, North Carolina. The congestion scores for recurring and non-recurring congestion were combined to evaluate the reliability of each link.

Data from loop detectors or other sources could be captured to model the affect of a crash at a location on travel time variation or other measures within its vicinity. However, crashes are random, comparatively rare events, and may occur at any point on the network. Several other factors could also play a role on real-time travel times along a corridor. Understanding the effect of a crash using simulation approach would help forecast variation over time (short-term) due to the same, minimize complexities that arise due to the presence of several other variables, and better plan to emulate dynamic message signs and influence travel patterns over space and time. Using a simulation approach to model the effect of crashes on travel time variation also has an inherent advantage. One need not rely entirely on travel time as a measure nor will model calibration be as critical.

Past research on travel time variation and upstream distance affected from the blocked section (crash location) due to a crash is limited. The effect of lane on which a crash has occurred and the formation and dissipation of queue over time was not explored in the past. This research focuses to bridge these gaps by examining travel time variation caused due a crash (by severity) and the lane on which the crash occurred.

3. Methodology

A ~10-mile, 6-lane freeway corridor (I-85 from Exit 33 to Exit 43) in the city of Charlotte, North Carolina was used as the study corridor to simulate and assess the effect of a crash on travel time variation over time along the corridor (Fig. 1). The duration of blockage, the length of lane(s) blocked, and the number of lanes blocked for fatal, injury and PDO crashes along Interstates play a vital role on system performance. Table 1 summarizes North Carolina Highway Safety Patrol's typical plan (estimates) to respond to a call, assist those involved in a crash, file a report, and clear the crash site. These details were used to define simulation scenarios.

Traffic heading northbound towards Concord/Kannapolis was considered for simulation and analysis. Traffic volume maps developed and maintained by the North Carolina Department of Transportation (NCDOT) indicate that the annual average daily traffic (AADT) along the corridor in the northbound direction (with 3 travel lanes) varied between 55,000 and 75,000 at the time of this study. Field observations indicated that 5000–6500 vehicles traversed along this corridor during the evening peak hour. However, different traffic volumes were considered to test the effect of traffic volume (indicative of different levels of service) on travel time variation and upstream distance affected due to a crash. Traffic volume during weekday traffic hours varied from ~2% to ~10% of AADT along the study corridor. While 1000 vehicles per hour (vph) was used to represent off-peak or uncongested low traffic volume condition (level-of-service A or B), 3000 vph and 6000 vph were used to represent moderate (level-of-service C or D) and relatively high traffic volume (congested; level-of-service E or F) conditions. The incoming traffic volume for onramps was considered as 10% of initial traffic volume and the outgoing traffic volume for offramp was considered as 1% of traffic volume on the previous section. Heavy vehicle percentages are not known and left as default values in this study. The traffic volumes considered per hour were assumed to stay constant for each simulation conducted in this research.

Table 1
Duration, length and lanes blocked by crash type.

Crash type	Duration (h)	Length of lane blocked (mile)	# of lanes blocked
Fatal	1	2	2
Injury	0.5	0.1	1
PDO	0.25	0.004	1

An aerial photo of the corridor was used as background image to create the network for simulation in VISSIM 5.30™ (PTV Vision, 2011) environment. The detailed geometric features such as lane widths, horizontal curves, shoulder width, channelization/pavement markings and locations of ramps were incorporated into the simulation model. Lane numbers were assigned from the right-most lane as 1 (ramps are connected to this lane) to the left-most lane as 3.

Traffic volumes were inputted at the start point of the corridor and at the entry ramps using "Vehicle Inputs" feature in VISSIM 5.30™. The percentages of traffic volume exiting the corridor were assigned to exit ramps using "Routes" feature in VISSIM 5.30™. Travel time segments with ~0.5-mile length were created along the corridor using "Travel Time Sections" feature available in VISSIM 5.30™. There are 20 travel time segments along the length of the selected corridor (length, as stated previously, is ~10 miles).

Simulations were first generated to test the model using traffic volume for the no crash condition (baseline condition). The United States Federal Highway Administration (FHWA)'s Traffic Analysis Toolbox recommends the use traffic volume (hourly flows), travel time and visual audits based criteria to test and calibrate a simulation model (Dowling et al., 2004). The simulated traffic volume for no crash condition was more than 85% of the input traffic volume for all the links. The visual inspection of the simulations showed acceptable speed-flow relationships for different traffic volumes. The crash was then simulated to occur between travel time segment 17 and travel time segment 18. The farthest travel time segment, upstream from the crash location, is travel time segment 1.

Overall, three different scenarios were considered for the analysis and simulation in VISSIM 5.30™. They are:

i No crash condition—traffic flows without any interruption; basic calibrated model;
ii Fatal crash condition—traffic flows with a fatal crash blocking two travel lanes on the corridor; the blocked lanes are re-opened for normal traffic flow 60 min after the fatal crash; and,
iii Injury crash condition—traffic flows with an injury crash blocking one travel lane on the corridor; the blocked lane is re-opened for normal traffic 30 min after the injury crash.

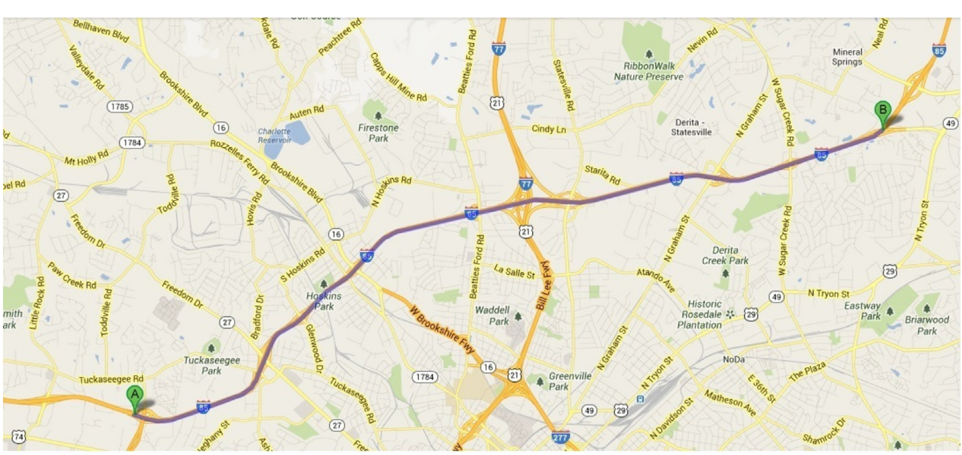

Fig. 1. Study corridor—I-85 from Exit 33 to Exit 43, Charlotte, NC.

In the first scenario, the traffic flows without any interruption as it is a no crash condition (baseline condition). There is no crash and lane blockage during this simulation. There were no restrictions laid to lane change and lane changing behavior along the corridor. The traffic flow might be interrupted due to recurring congestion (traffic volume, merging and diverging maneuvers). As stated previously, separate simulations were conducted using traffic volume of 1000 vph, 3000 vph and 6000 vph for the same network.

The traffic flow was interrupted by a fatal crash in the second scenario. When a fatal crash occurs on a corridor, two lanes are blocked for a period of one hour over a length of 2 miles from the fatal crash location. Therefore, during the simulation, two lanes were blocked 15 min after the start of simulation. The lane blockage lasted for 1 h. Separate simulations were conducted using traffic volume of 1000 vph, 3000 vph and 6000 vph for the same network. The effect of fatal crash between Exit 41 and Exit 42 (between travel time segment 17 and travel time segment 18) on the right-most lane 1 as well on the left-most lane 3 was simulated and examined to assess the effect of lane on which a fatal crash has occurred on travel time variation.

The traffic flow was interrupted by an injury crash in the third scenario. When an injury crash occurs on a corridor, one lane is blocked for a period of 30 min over a length of 500 feet from the injury crash location. Therefore, during the simulation, one lane was blocked 15 min after the start of simulation and this lasted for 30 min. Like in the previous scenario, separate simulations were conducted using traffic volume of 1000 vph, 3000 vph and 6000 vph for the same network. The effect of injury crash between Exit 41 and Exit 42 (between travel time segment 17 and travel time segment 18) on each lane was simulated and examined to assess the effect of lane on which a injury crash has occurred on travel time variation.

The total simulation period for the above defined scenarios was 3 h. However, travel time outputs were generated and compared for 15 min intervals.

The simulation software's user manual recommends a minimum of 5 runs depending on the type of application (PTV Vision, 2011). Five simulations were conducted with random seeds 1, 11, 21, 31, and 41. The variability in travel time estimates for the "no crash scenario" was examined. The standard deviations are less than or equal to 10% of the mean for almost all the travel time estimates in case of low and moderate traffic volume conditions but for a majority of travel time estimates in case of high traffic volume condition. Overall, these results indicate that considering five seed numbers provided reasonably accurate estimates for the subject problem. The average of travel time values obtained after simulations using the five random seeds were computed for each scenario and considered for assessment.

Travel time variation was computed, at 15 min intervals for the three hour simulation period, by comparing travel time along a segment during a crash scenario with travel time along the same segment during no crash scenario. The variation in travel time was computed for different traffic volume and lanes on which a crash has occurred condition. The use of travel time variation not only helps capture the effect of only crash but also minimizes any other possible errors not considered in the calibration process (example, motorist behavior).

Table 2
Travel times (in seconds) over time and space—no crash condition.

Time	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Traffic volume = 1000 vph																				
15 min	27	27	27	27	31	35	35	38	38	40	43	45	46	46	46	48	49	50	51	50
30 min	27	27	27	27	31	34	34	37	37	40	42	44	46	46	46	47	48	50	50	51
45 min	27	27	27	27	31	34	34	36	37	40	42	45	46	46	46	48	48	50	51	52
60 min	27	27	27	27	31	34	34	37	37	39	42	44	47	47	47	48	49	50	50	50
75 min	27	27	27	27	31	34	34	37	37	40	42	44	46	46	47	49	50	52	52	53
90 min	27	27	27	27	31	34	35	37	38	40	42	45	46	46	47	49	48	50	51	50
105 min	27	27	27	27	31	35	35	38	38	41	43	45	46	47	47	49	50	52	51	51
120 min	27	27	27	27	31	34	34	37	37	40	43	44	46	46	46	48	48	50	51	52
135 min	27	27	27	27	31	35	35	38	38	41	43	45	47	47	47	48	49	50	50	51
150 min	27	27	27	27	31	34	35	38	38	40	43	45	46	47	47	49	49	51	51	51
Traffic volume = 3000 vph																				
15 min	27	28	28	30	34	37	40	45	47	52	56	59	62	64	64	68	67	68	66	66
30 min	27	28	28	30	34	38	41	46	49	53	57	60	63	66	65	68	68	71	67	68
45 min	27	28	28	30	34	38	40	46	48	54	58	61	63	67	66	67	67	69	67	68
60 min	27	28	28	30	34	38	40	45	46	51	56	60	63	67	65	67	66	68	68	68
75 min	27	28	28	30	33	36	39	43	46	51	57	60	64	67	65	69	66	68	67	68
90 min	27	28	28	30	34	38	40	44	46	52	57	59	61	64	65	69	67	71	67	68
105 min	27	28	28	30	34	38	40	44	46	50	57	61	63	65	65	66	68	69	68	67
120 min	27	28	28	30	34	39	41	46	48	52	56	59	61	67	65	68	68	71	68	68
135 min	27	28	28	30	34	37	39	43	45	50	56	60	63	65	66	70	67	70	68	68
150 min	27	28	28	30	34	37	39	44	46	51	56	59	61	64	64	66	66	68	67	68
Traffic volume = 6000 vph																				
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
15 min	29	30	35	75	88	82	78	82	77	73	66	67	70	74	68	71	69	72	68	68
30 min	30	49	104	112	104	94	84	83	82	82	67	70	73	76	71	71	68	73	69	68
45 min	87	120	126	115	107	91	88	89	83	76	65	69	75	77	69	70	71	72	68	67
60 min	136	140	141	122	104	83	84	84	77	69	66	69	71	74	70	72	72	74	68	67
75 min	121	113	115	105	99	88	82	83	82	80	67	71	75	77	69	70	69	72	68	67
90 min	118	120	127	120	114	109	93	90	83	77	66	69	72	75	68	69	70	71	67	67
105 min	135	132	133	117	103	92	83	86	80	76	64	67	70	73	68	70	70	72	68	67
120 min	125	123	127	115	109	103	92	89	86	82	65	66	68	71	68	70	69	71	68	67
135 min	132	130	133	119	105	93	85	86	82	82	66	66	69	72	70	72	71	73	68	67
150 min	122	123	129	119	108	92	84	84	79	82	66	73	75	78	69	71	70	71	68	67

Note: Traffic is moving from travel time segment 1 towards travel time segment 20.

The upstream links with continuous variation in travel time were identified to estimate the upstream distance affected due to a crash on the corridor. Based on the way the travel time segments were numbered, lower travel time segment number with variation indicates longer the effect on travel time variation due to a crash. The travel time variation for each segment over time was plotted to examine queue formation and dissipation patterns.

4. Results

Table 2 summarizes travel times (average from the five random seeds) for various travel time segments over time for the no crash condition. Marginal differences in travel times were observed when traffic volume is increased from 1000 vph. However, the travel times were generally very high for most of the segments when traffic volume is 6000 vph (due to increasing congestion over the simulation period).

A discussion on travel time variation over time, upstream distance affected over time, and travel time variation over distance is discussed in this section. The results obtained for different traffic volumes and lanes on which the crash occurred are discussed as well.

4.1. Travel time variation over time

The travel time variation due to a fatal crash increased till all blocked lanes were re-opened for traffic (maximum travel time variation occurred 60 min after the crash) and then followed a decreasing trend in case of low, moderate and high traffic volume (Fig. 2). Normal traffic conditions were restored 75 min, 150 min and 105 min after the fatal crash on the right-most lane (Fig. 2a) when traffic volume was 1000 vph, 3000 vph and 6000 vph, respectively. On the other hand, normal traffic conditions were restored 75 min, 120 min and 105 min after the fatal crash on the

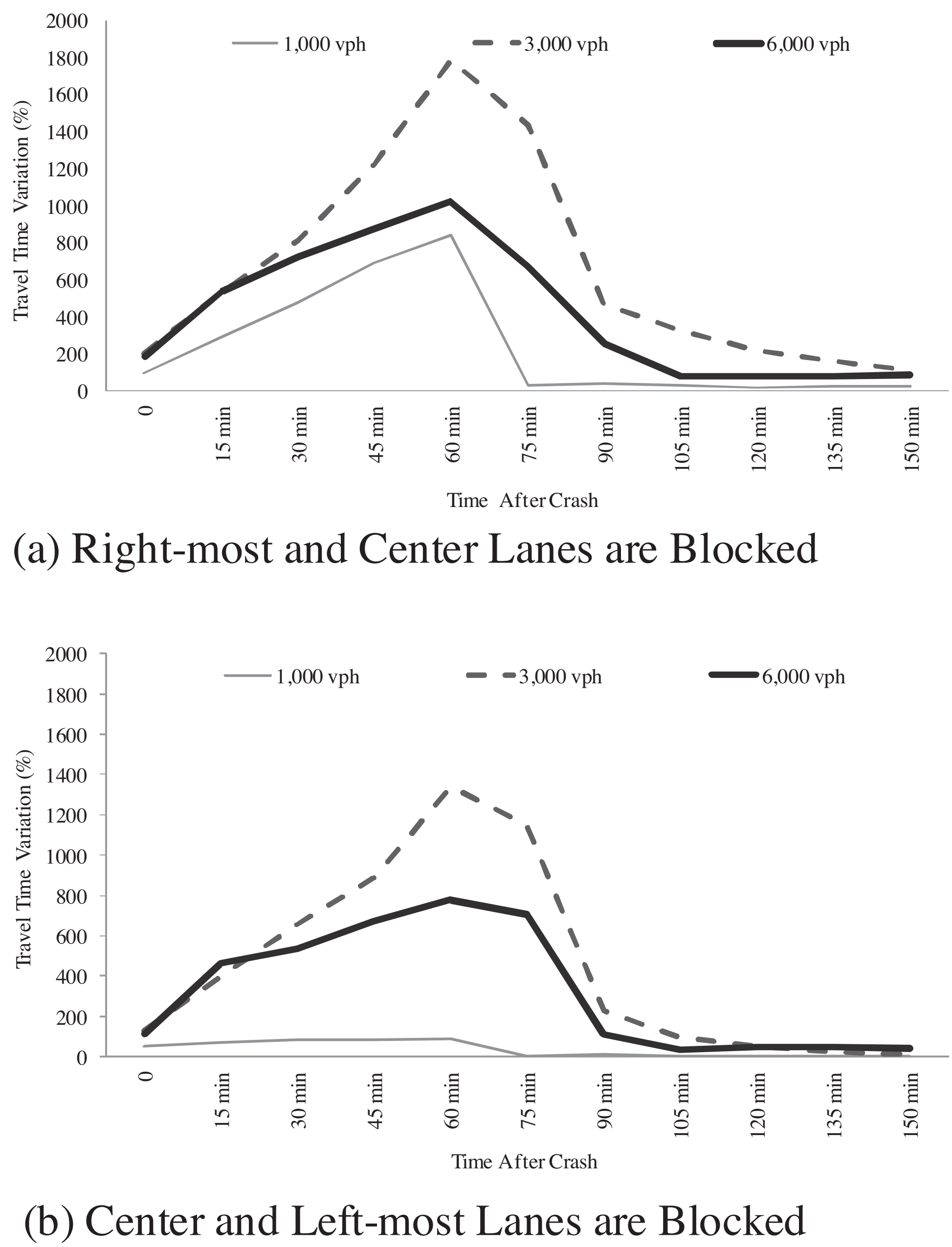

Fig. 2. Travel time variation over time due to a fatal crash.

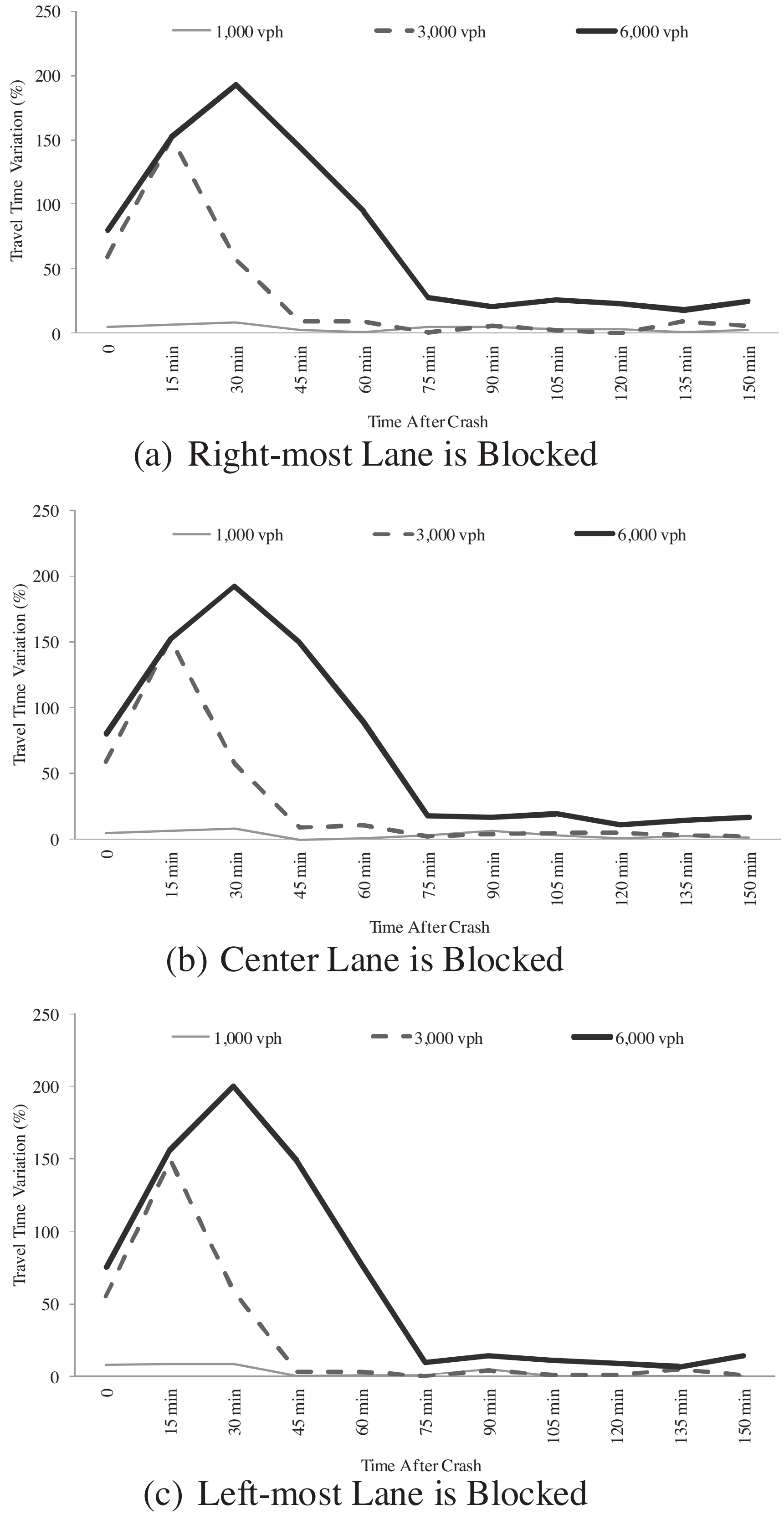

Fig. 3. Travel time variation over time due to an injury crash.

left-most lane (Fig. 2b) when traffic volume was 1000 vph, 3000 vph and 6000 vph, respectively.

Travel time variation for an injury crash increased till the blocked lane was re-opened for traffic and then followed a decreasing trend in case of high traffic volume, whereas it followed a decreasing trend 15 min after the injury crash occurred in case of moderate traffic volume (Fig. 3). Normal traffic conditions were restored 45 min and 75 min after the injury crash when traffic volume was 3000 vph and 6000 vph, respectively. There was no variation in travel time due to an injury crash in case of low traffic volume (Fig. 3). Similar trends were noted irrespective of the lane on which the injury crash occurred. The travel time variations seem to be marginally higher when the crash was simulated on the right-most lane (close to ramps) than when compared to the center or left-most lane.

Overall, fatal crash on freeways has an effect under low, moderate and high traffic volume conditions, whereas injury crash has an effect only under moderate and high traffic volume conditions. In case of fatal crash, non-recurring congestion effects in terms of travel time variation are high for moderate traffic volume than when compared to high traffic volume. The relative effect of fatal crash during high traffic volume was less when compared with moderate traffic volume because the road network was already congested (unreliable) due to high traffic volume, leading to a relatively lower travel time variation when compared to the no crash condition.

The difference in travel time variation along the segments between the fatal crash on the right-most and left-most lanes varied from 200% to 500%. The travel time variation due to a fatal crash on the right-most lane was generally greater than fatal crash on the left-most lane (Fig. 2). The reason for the large variation might be due to the fact that, when the lanes near ramps were blocked, the vehicles entering the freeway through the onramp and planning to exit through the offramp were not allowed to enter and merge with the mainstream traffic along the length of the blocked section.

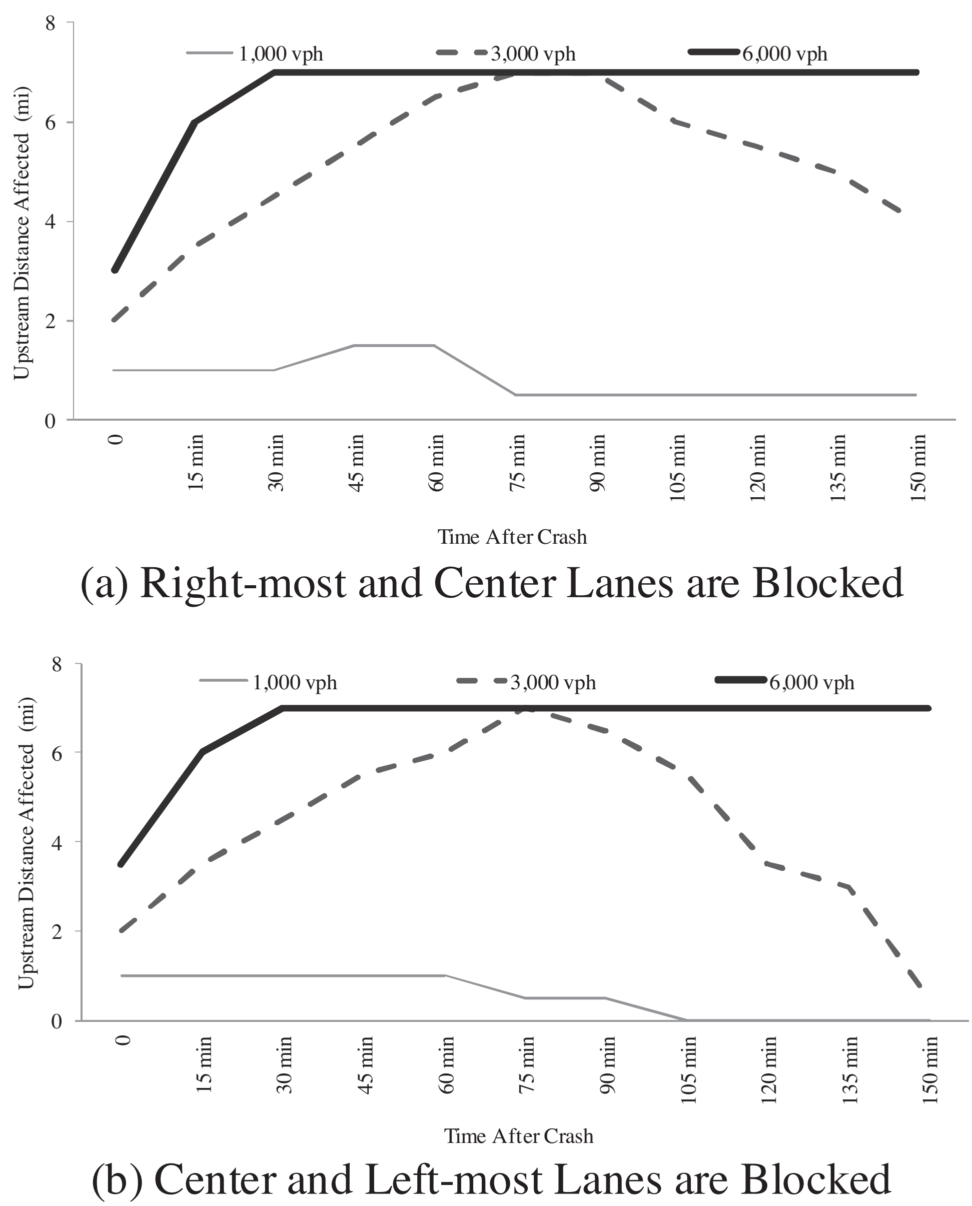

Fig. 4. Upstream distance affected from the blocked section over time due to a fatal crash.

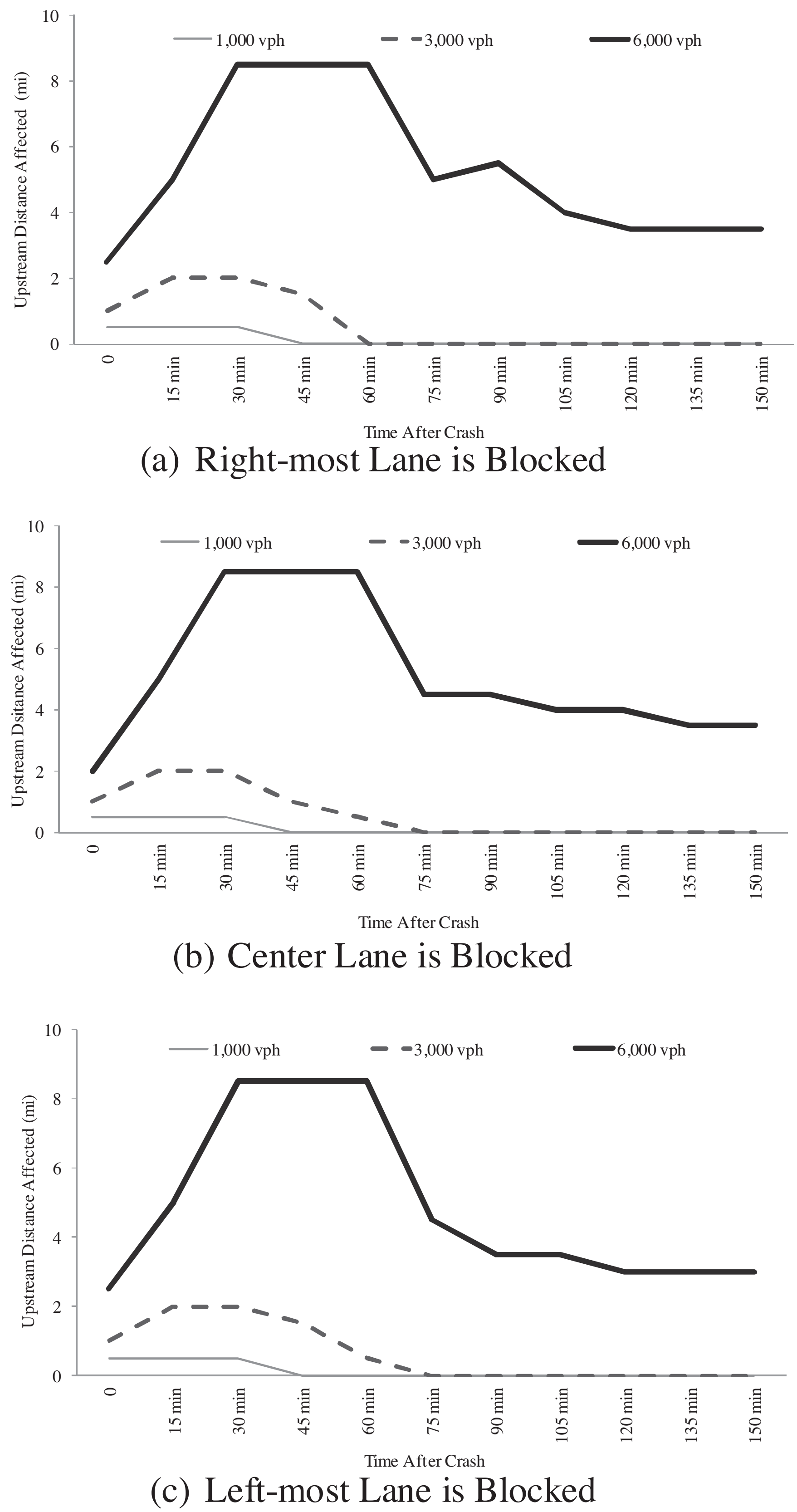

Fig. 5. Upstream distance affected from the blocked section over time due to an injury crash.

4.2. Upstream distance affected over time

The upstream distance affected from the blocked section due to a fatal crash followed a similar trend irrespective of whether the crash occurred in the right-most or left-most lanes (Fig. 4). The only exception being when traffic volume was 3000 vph, where the maximum distance affected stayed constant for about 15 min when the fatal crash occurred in the right-most lane, whereas it decreased immediately after touching the peak when the fatal crash occurred in the left-most lane.

In case of a fatal crash and traffic volume was 1000 vph, the upstream distance affected increased to ~1.5 miles over time when the fatal crash occurred on the right-most lane (Fig. 4a), whereas it increased to ~1 mile when the fatal crash occurred on the left-most lane (Fig. 4b). A decreasing trend in total upstream distance affected was observed 75 min after the fatal crash (when blocked lanes were re-opened for normal traffic flow).

In case of a fatal crash and traffic volume was 3000 vph, the total upstream distance affected from the blocked section increased from ~2 miles to ~7 miles 75 min after the fatal crash (Fig. 4). While a decreasing trend was observed after 90 min, the total upstream distance affected was about 4 miles and 0.5 miles at the end of simulation period when the fatal crash occurred on right-most and left-most lanes, respectively.

In case of a fatal crash and traffic volume was 6000 vph, all upstream links were affected 30 min after the fatal crash. They continued to be affected for about 2.75 h. Normal conditions may not be restored unless there is decrease in traffic volume, clearly indicating benefits that could be achieved by influencing travel patterns using dynamic message signs.

The total upstream distance affected from the blocked section due to an injury crash followed a similar trend irrespective of whether the injury crash occurred in the right-most, center or left-most lane (Fig. 5). As was observed previously, the effect seem to be marginally higher when the crash was simulated on the right-most lane (close to ramps) than when compared to center or left-most lane.

In case of an injury crash and traffic volume was 1000 vph, the total upstream distance affected from the blocked section was ~0.5 miles. A decreasing trend in total upstream distance affected was observed 45 min after the injury crash (when the blocked lane was re-opened for normal traffic flow). When traffic volume was 3000 vph, the total upstream distance affected from the blocked section increased from ~1 mile to ~2 miles. A decreasing trend in total upstream distance affected was observed 45 min after the injury crash even in this case. In case of an injury crash and traffic volume was 6000 vph, the total upstream distance affected from the blocked section increased from ~2.5 miles to ~8.5 miles. A decreasing trend in total upstream distance affected was observed 75 min after the injury crash in this case.

4.3. Travel time variation over distance—queue formation and dissipation

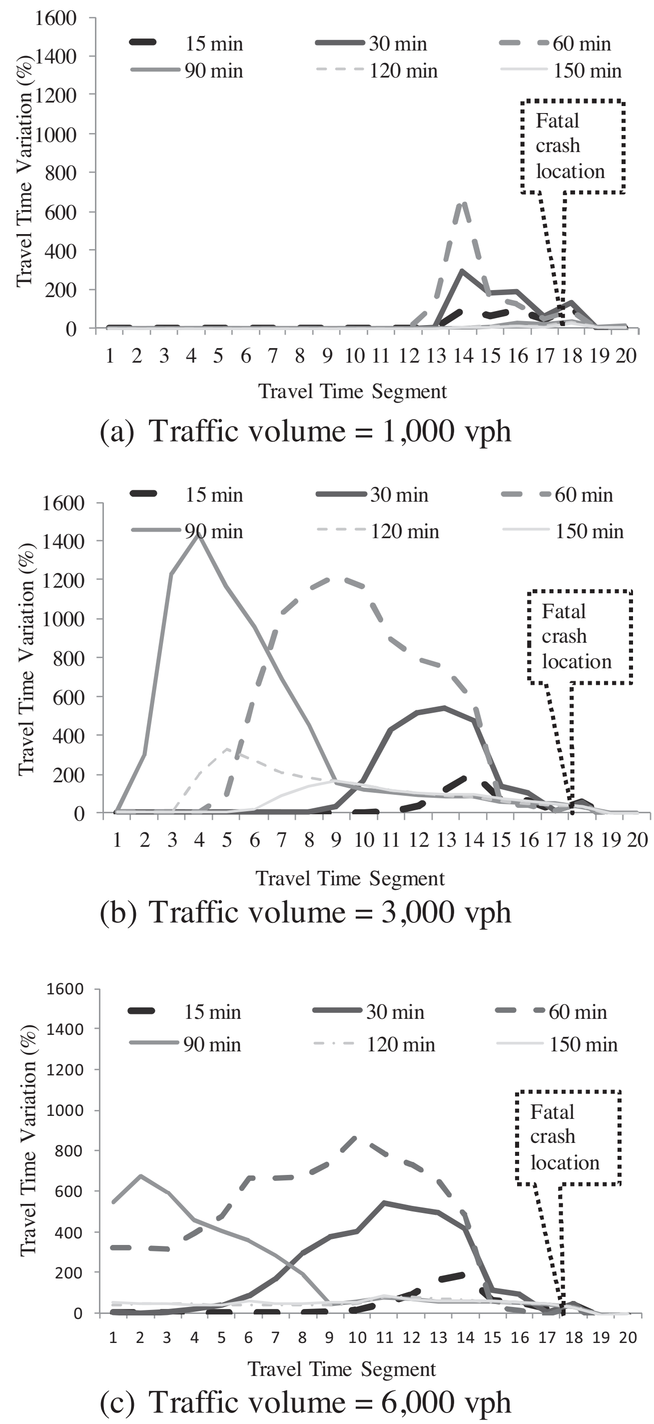

Fig. 6. Travel time variation over distance due to a fatal crash.

The formation and dissipation of queue for each scenario and condition was assessed based on travel time variation over distance and time. Fig. 6 shows travel time variation by travel time segment over time due to a fatal crash for different traffic volumes. Travel time variation along the segment 15 min, 30 min, 60 min, 90 min, 120 min and 150 min after the crash are shown in the figure. As stated previously, the blocked lanes were re-opened for normal traffic flow 60 min after the occurrence of a fatal crash. The travel time variation was observed to increase till 60 min after the fatal crash irrespective of the traffic volume.

When traffic volume was 1000 vph, the queue dissipated in 45 min after the blocked lanes were re-opened for normal traffic flow in case of a fatal crash in the left-most lane. The increase in the upstream distance affected for low traffic volume was marginal in this case.

When traffic volume was 3000 vph, the travel time variation was observed till travel time segment 12 at the end of first 15 min after the fatal crash. The travel time variation extended to travel time segments 9, 5 and 1 at the end of 30 min, 60 min and 90 min, respectively after the fatal crash. A closer observation shows higher travel time variation (formation of the queue and additional delay) along upstream travel time segments (4 to 1) though the queue has been dissipating from travel time segment 16 to travel time segment 5 due to re-opening of lanes for normal traffic flow 60 min

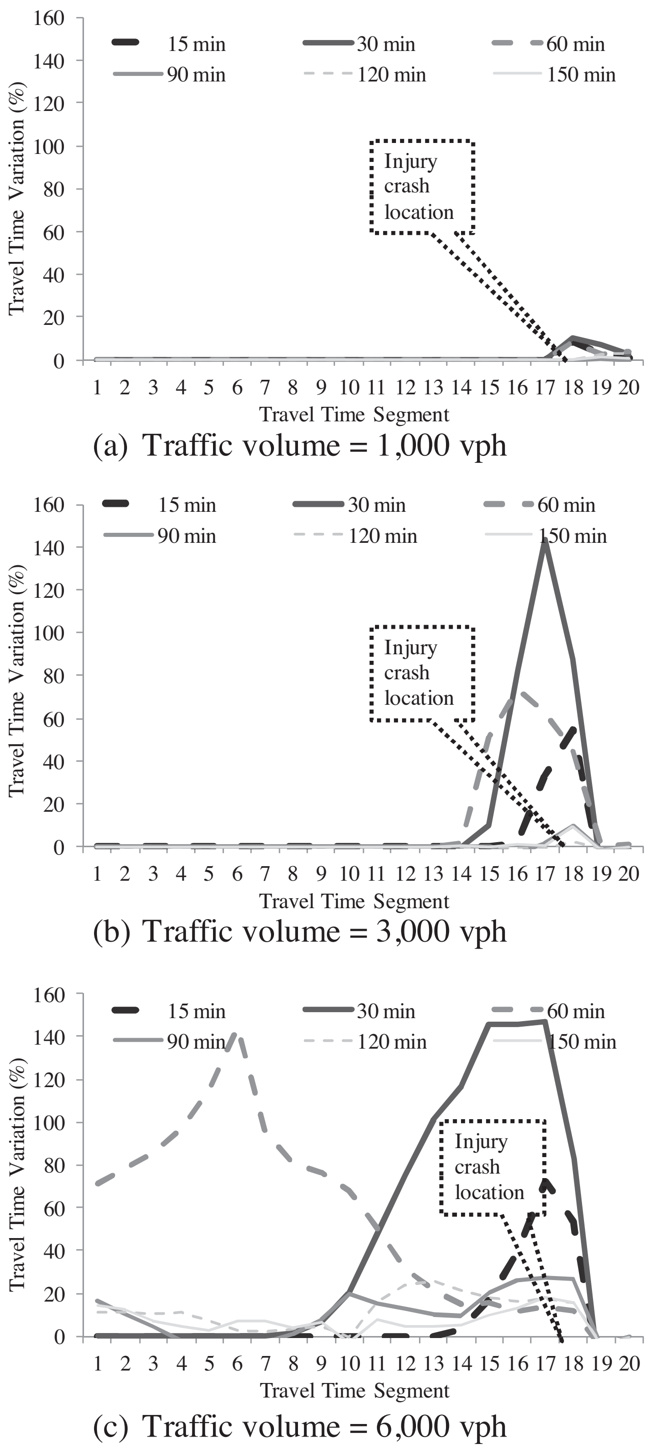

Fig. 7. Travel time variation over distance due to an injury crash.

after the fatal crash. As stated previously, this is because queue is building in the upstream direction (towards segment 1) but dissipating at a faster rate in the same direction.

When traffic volume was 6000 vph, the travel time variation was observed till travel time segment 9 at the end of 15 min after the fatal crash. The travel time variation extended to travel time segment 4 and beyond 30 min after the fatal crash. Like in the previous case, higher travel time variation (formation of queue and additional delay) was observed along upstream travel time segments (4 to 1) though the queue has been dissipating from travel time segment 16 to travel time segment 5 due to re-opening of lanes for normal traffic flow 60 min after the fatal crash.

Fig. 7 shows travel time variation by travel time segment over time due to an injury crash for different traffic volumes. The travel time variation was observed to increase till 30 min after injury crash irrespective of the traffic volume. The effect was minimal when travel volume was 1000 vph. When traffic volume was 3000 vph, the travel time variation was only observed till travel time segment 15. The dissipation seems to, as expected, occur at a faster rate. However, when traffic volume was 6000 vph, the travel time variation was observed till travel time segment 15 at the end of first 15 min after the injury crash. The travel time variation extended to travel time segment 9 at the end of 30 min after the fatal crash. A closer observation shows higher travel time variation (formation of the queue and additional delay) along upstream travel time segments (6 to 1) though the queue has been dissipating from travel time segment 16 to travel time segment 7 due to re-opening of lanes for normal traffic flow 30 min after the injury crash.

5. Conclusions

An evaluation and assessment of travel time variation and upstream distance affected due to a fatal or injury crash on a freeway corridor is presented in this paper. Observations from simulations show that fatal crash on freeways has an effect under low, moderate and high traffic volume conditions, whereas injury crash has an effect only under moderate and high traffic volume conditions. The relative variation in travel time is higher for moderate traffic volume or uncongested conditions than when compared to high traffic volume or congested conditions. Therefore, it can be concluded that non-recurring congestion plays a vital role along with recurring congestion and should be taken into account to quantify overall congestion.

Non-recurring congestion measures when combined with recurring congestion measures will increase the reliability in assessing the congestion levels for a road network. Hence, incorporating the effect of a crash on travel time variation, when assessing the reliability of road network, will result in application of a better performance measure for quantifying congestion.

The travel time variation and upstream distance affected due to a fatal crash on the right-most lane is generally greater than a fatal crash on the left-most lane. The trends are fairly consistent irrespective of the lane on which an injury crash occurred.

The maximum upstream distance affected due to a fatal crash is ~1.5 miles over time when traffic volume is 1000 vph, whereas it is ~7.5 miles over time when traffic volume is 3000 vph or 6000 vph. In case of an injury crash, the upstream distance affected is ~0.5 miles, 2 miles and ~7.5 miles over time when traffic volume is 1000 vph, 3000 vph and 6000 vph, respectively.

In case of a fatal crash (irrespective of the lane in which it occurred), queue starts dissipating 15 min after blocked lanes are re-opened for normal traffic flow when traffic volume is 1000 vph. When traffic volume is 3000 vph, queue starts dissipating 45 min and 30 min after blocked lanes are re-opened for normal traffic flow if the fatal crash occurs in the right-most lane and left-most lane, respectively. Unless there is a reduction in traffic volume, queue dissipation may not happen in case of a fatal crash (irrespective of the lane in which it occurred) and traffic volume is 6000 vph. Queue starts dissipating 15 min after blocked lanes are re-opened for normal traffic flow when traffic volume is 1000 vph and 3000 vph in case of an injury crash (irrespective of the lane in which it occurred). When traffic volume is 6000 vph, queue starts dissipating 45 min after blocked lanes are re-opened for normal traffic flow irrespective of the lane in which it occurred.

Traffic simulation software and method adopted in this paper could be used to evaluate and assess the effect of a crash on travel time variation over time and space. For a practitioner, information about the upstream distance affected from the blocked section versus traffic volume could be used to study the queue building and dissipation patterns due to a crash (by severity or number of lanes blocked). As an example, motorists 2 miles from a fatal crash location may be informed about potential delay 15 min after the fatal crash occurrence while motorists 8 miles from the fatal crash location may be informed about potential delay 60 min after the fatal crash occurrence. Disseminating such timely information about the length and duration of congestion ahead, depending on the severity of crash, through the use of dynamic message signs will alert motorists and influence travel patterns over time.

Simulations and analyses are required to examine the effect of primary and secondary crashes on congestion. The length of the blocked section could also vary based on where the crash occurred. Motorists may divert to alternate routes based on information provided through dynamic message signs. This could have an effect on network performance and risk along alternate routes. Incorporating such aspects, in addition to motorist behavior under recurring and non-recurring congestion conditions, to realistically assess network performance using the simulation process merits further investigation. A comparison using real-world data would also ascertain the outcomes and justify its applicability for implementation.

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