Impact of Connected Vehicle on Work Zone Network Safety through Dynamic Route Guidance

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Abstract: Despite enhanced safety strategies, in-vehicles technologies, and improvements in infrastructure, urban transportation networks are still accident-prone. Connected vehicle offers the possibility to exchange data with vehicles and infrastructure in an effort to improve safety. The main objective of the research reported in this paper is to evaluate the potential safety benefits of deploying a connected vehicle system on a traffic network in the presence of a work zone. The modeled connected vehicle system in the research reported in this paper uses vehicle-to-vehicle (VTV) communication to share information about work zone links and link travel times. Vehicles which receive work zone information will also modify their driving behavior by increasing awareness and decreasing aggressiveness. This paper also proposes a decaying average travel time dynamic route guidance algorithm which exhibits weighted information decay. Traffic microsimulation software is used to model the network and a C plugin is developed to implement connected vehicle in the simulation. The surrogate safety measure improved time to collision (TTC) is used to assess the safety of the network. Various market penetrations of connected vehicles were utilized along with three different behavior models to account for the uncertainty in driver response to connected vehicle information. The results show that network safety is strongly correlated with the behavior model used; conservative models yield conservative changes in network safety. The results also show that market penetrations of connected vehicles under 40% contribute to a safer traffic network, while market penetrations above 40% decrease network safety. The findings of the research reported in this paper indicate connected vehicle technology can have unintended consequences, as seen in decreased safety at high market penetrations, requiring researchers to develop additional applications to mitigate these effects. **DOI: 10.1061/(ASCE)CP.1943-5487.0000490.** *© 2015 American Society of Civil Engineers.*

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Introduction

Connected Vehicle is a U.S. DOT program that facilitates data exchange between vehicles and infrastructure to improve safety, mobility, and reduce the environmental impact of transportation (USDOT 2013). The foundation of Connected Vehicle is the ability for vehicles to establish ad-hoc, wireless communication networks. Connected vehicles use wireless communication technologies to collect, transmit, and receive pertinent transportation information such as vehicle position, velocity, and travel time. Data exchanged between vehicles will be analyzed and used in connected vehicle applications such as dynamic route guidance and work zone hazard warnings; the research reported in this paper aims to determine the effect of these applications on network safety. Vehicle-to-vehicle (VTV) communication is a connected vehicle technology which enables information sharing between vehicles by means of wireless communication. A work zone can be defined as, "... an area of a trafficway with highway construction, maintenance, or utility-work activities. A work zone is typically marked by signs, channeling devices, barriers, pavement markings, and/or work vehicles" and described, "... (to exist) for short or long durations and may include stationary or moving activities" (Turner 1999). Work zones can introduce variance in speed and traffic behavior; with variance in traffic speed being an important predictor for accidents (Garber and Woo 1990). Numerous methods are currently used to improve safety around work zones. These methods include, but are not limited to, flaggers, static/variable message signs, dynamic lane merging systems, variable speed limits, and temporary traffic control signals (Li and Bai 2009). Connected vehicle technologies have the potential to improve traffic safety around work zones beyond the ability of the previously mentioned methods through their real-time data collection, sharing, and various applications.

Compared to current real-time traffic applications, such as Google Maps and Waze, connected vehicle differs in a few key ways. First, current real-time traffic applications collect data through a surrogate device, often a smartphone, in the form of global positioning system (GPS) location data (Google 2009; Waze 2014). This data is used to determine a vehicle's velocity, a coarse source of information with limited data resolution. This GPS data is filtered through algorithms which remove outliers and generates useable information. Connected vehicles have direct access to the current state of the vehicle, being able to share more accurate information, as there is no gap between the information source (vehicle) and the information sharing (smartphone); by default connected vehicles are equipped with wireless communication capabilities. Connected vehicles would not only be able to share their speed and direction, but also additional information such as fuel consumption and current weather conditions (temperature and humidity). Another difference is that connected vehicles can function without the support of a large infrastructure, establishing VTV, ad-hoc, decentralized networks when sufficient market penetrations are achieved. Current applications such as Google Maps require a large network backbone independent of the data sources; if the backbone is down or a connection is unavailable, the application

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will not function. However, having access to a large network infrastructure has benefits such as intense computation can be offloaded to the network and then transmitted back to the clients. Connected Vehicle has also been designed to interface with a large, independent infrastructure, in the form of vehicle-to-infrastructure (VTI) communication.

The research reported in this paper differs from previous studies (Kang et al. 2004; Outcalt 2009) in that it is uses a mobility focused method, dynamic route guidance with work zone penalties, to examine connected vehicle's effect on traffic safety in and around construction work zones. Connected vehicles' communication of travel times and work zone information is used as input for dynamic route guidance, which seeks to minimize travel time on route to their destination. Once a connected vehicle has discovered the work zone and propagated this information to other connected vehicles, connected vehicles will traverse routes that bypass the work zone. The approximate safety impacts of this routing decision on the work zone, which will change as different simulations are executed with various market penetrations of connected vehicles, will be compared to a control simulation where no connected vehicles exist. Prior research has studied VTV and traffic safety (Azimi et al. 2011; Xu et al. 2011; Sepulcre and Gozalvez 2012), dynamic route guidance (Chen et al. 2010; Khosroshahi et al. 2011), and other research has studied work zones (Ha and Nemeth 1995; Pal and Sinha 1996; Khattak et al. 2002). However, there is a gap in using the specific technological characteristics of Connected Vehicle (VTV communication) in conjunction with dynamic route guidance and work zones. Previous studies have not integrated dynamic route guidance, VTV communication, and work zones together. The research reported in this paper brings all of these elements together in microsimulation and examines the effects on traffic safety.

The objective of the research reported in this paper is to assess the impact of connected vehicle technologies, specifically VTV communication, work zone hazard warnings, and dynamic route guidance, on traffic safety in a traffic network with a work zone present. *Paramics*, a transportation microsimulator, was used to model a traffic network and simulate the connected vehicle applications and VTV communication. A custom C plugin in conjunction with the *Paramics*' application programming interface (API) was developed to implement the connected vehicle applications and VTV communication. The API is also responsible for collecting statistics associated with the safety index of the improved time to collision (TTC) surrogate safety measure (Bachmann et al. 2010), and implementing the work zone. The research reported in this paper ventures to understand how traffic safety is affected by the use of a connected vehicle system in the presence of a work zone.

Literature Review

Connected vehicle technology has the potential to improve traffic safety, mobility, and environmental impacts. Transportation (2013) describes dynamic route guidance as a proactive approach to manage congestion, whereby vehicles are advised to reroute to arterial and less-congested routes to increase traffic mobility and subsequently safety. Connected vehicles have the potential to use the data they exchange in their dynamic route guidance calculations to help balance traffic in a network, reduce congestion, and reroute to avoid work zones. Kattan et al. (2010) investigated the impact of VTV-equipped vehicles on a network with random incidents. They developed APIs to facilitate the generation of random incidents according to collision and inclement weather probabilities along with simulating VTV communication. Vehicles that become notified of incidents increase their awareness and decrease their aggressiveness. Kattan et al. (2010) found an overall improvement in network performance, with a decreased collision probability and decrease in path travel time for VTV and non-VTV vehicles. Various intelligent transportation systems' research studies have already yielded promising results. Abdulhai and Look (2003) investigated the effects of dynamic route guidance on traffic safety using microsimulation. Their simulation consisted of two vehicles types, as follows: (1) a set that was considered uninformed and did not have access to real-time information regarding network conditions, and (2) a set that had their cost-to-destination tables updated every 5 min to reflect the present network conditions and sought to traverse the shortest travel time path to their destination. Results from their study showed that higher percentages of informed vehicles of the total vehicle population led to a reduction in average travel time, an increase in vehicle throughput but also an increase in total incidents. Lee et al. (2013) has conducted research on connected vehicle applications, specifically expanding on previous efforts to develop a cooperative vehicle intersection control (CVIC) algorithm. This application would control the signal timings at intersections to increase mobility, attempting to reduce or eliminate stop-and-go traffic conditions. Their results showed when compared to the coordinated, actuated signal control, the CVIC algorithm significantly reduced delays along with reducing the number of rear-end crash event by 30–87%, improved air quality (12–36% CO_2 emission reduction), and reducing fuel consumption by 11–37%.

Chen et al. (2014) developed and tested a new travel time snapshot estimation protocol, termed the R^2 protocol. The R^2 protocol was found to be more accurate than other conventional protocols and required fewer snapshots. Fitch et al. (2014) presents findings from experiments with connected vehicle collision avoidance systems. Subjects from their experiments who received forward collision warnings and lane change warning alerts were significantly faster at responding than compared to receiving only the forward collision warning alert. Jeong et al. (2014) proposed a novel means to manage driver inattentiveness, the intervehicle safety warning information system (ISWIS). This system uses the various sensors available in a connected vehicle environment to warn drivers' of impending hazards. Jeong et al. (2014) used *VISSIM* to test their ISWIS and results showed an increase in traffic safety using this system. Talebpour et al. (2014) introduce two detection algorithms to identify near-crashes in vehicle trajectory using interdriver heterogeneity, situation dependency, and connected vehicles. Their findings prescribe the importance of considering drivers' personal preference in near-crash algorithms and that near-crashes are likely to occur at high densities. Work zones often decrease total capacity of a roadway; introducing congestion, disrupting traffic, and introducing variations in speed and acceleration.

Many research efforts have been completed focusing on work zones. McCoy and Pesti (2001) proposed a new technique, the dynamic late merge, to address accident potential and congestion for work zone lane closures in rural areas. Ghosh-Dastidar and Adeli (2006) created a neural network-wavelet microsimulation model to estimate the travel time and queue length around work zones. Their new model was much more accurate than macroscopic models and significantly more efficient than microscopic simulation. Lin et al. (2004) proposed and simulated two variable speed limit controls at highway work zones. Analysis of the simulation results displayed the ability of variable speed limits to increase vehicle throughput and reduce vehicle delays, along with lower variances in vehicle speed around work zones. Maitipe (2011) proposed and field tested a dedicated short-range communications (DSRCs) VTI/VTV work zone traffic information system capable of disseminating travel times and locations of vehicle congestion to drivers. The proposed system uses work zone roadside units to share information with vehicles. Field trials showcased the ability of the system to adapt dynamically to changing traffic conditions while still transmitting traffic information to drivers.

Bushman et al. (2004) conducted a study in 2003 in South Carolina to determine the effectiveness of smart work zones on driver route decisions. The researchers used variable message signs to inform drivers of preceding traffic conditions in an effort to reroute them to prevent queues and delays. Analysis of the results showed the system was able to divert traffic to alternate routes without work zones present, producing the desired effect of reduced congestion. Mattox et al. (2007) sought to develop an affordable system to reduce vehicle speed in work zones. Their research led them to develop a speed-activated sign which informed the driver through a roadside visual cue if they were exceeding the speed limit in the work zone. The outcome of the research reported in this paper showed that the speed-activated sign had a significant impact on lowering the speed of vehicles in work zones. Rämä (1999) researched the effect that a variable speed limit, determined by information measured from weather stations, had on traffic safety. When inclement or adverse weather conditions were detected, the speed limit would be reduced. Increased traffic safety was achieved with weather-controlled speed limits by decreasing vehicle speed variance and mean speed. Although traffic safety was improved, Rämä (1999) noted the system was not socioeconomically profitable with the results achieved due to low traffic volume; areas of high traffic volume could potentially benefit more.

Variable message signs (VMSs) are large digital displays placed strategically beside roadways presenting drivers with brief traffic information, such as an upcoming work zone or expected delays. Variable message signs are the predominant method of communicating information to drivers and can be autonomous/embedded systems, receiving no input, or connected to a traffic control center. Chatterjee and McDonald (2004) analyzed the results from nine studies over 5 years from various European Union members to gauge the effectiveness of variable message signs at data dissemination and the information's effect on traffic. Their research showed that 0–31% of drivers diverted from their route when presented with variable information and a 1–2% reduction in average vehicle travel time was achieved in normal congestion. Erke et al. (2007) studied how drivers respond to variable message signs in regards to rerouting. Their results showed that variable message signs helped to reroute traffic but did demand attention and cognitive resources from drivers, a trade which may not be equitable to improve traffic safety. Horowitz et al. (2003) detailed results of research gauging the effect of variable message signs in diverting drivers away from routes with work zones. Their variable message signs displayed real-time estimates of travel times through the work zone and distance to the end of the work zone. Analysis of the results showed between 7 and 10% of traffic diverted to alternate routes depending on time of day and day of the week. Bushman et al. (2008) focused on developing a probabilistic analysis framework model for performing a cost benefit analysis of deploying smart work zones. Applying this framework to a case study in North Carolina, the benefit:cost ratio was between 1.2 and 11.9, indicating significant benefits to improving traffic conditions and driver's experience. Recently, a hybrid DSRC-portable changeable message sign (PCMS) system was developed and tested by Ibrahim and Hayee (2013) to inform drivers about work zones and warn them of nearby snowplows.

Even though there is ample research that various modern technologies can improve transportation safety and mobility, previous literature reviews conducted by Litman (2004) and Chorus et al. (2006) cautions transportation researchers that their estimates regarding travel information influence on drivers may be overly optimistic. Although it may be assumed that when a driver is presented information they will act on it, human behavior is not so predictable. Therefore future traffic research should not only focus on data collection and dissemination, but also how to make the data as appealing to drivers as possible. Microsimulation alone does not provide adequate models of traffic to investigate these issues; other fields of research need to be incorporated, such as cognitive/behavioral studies, in tandem with realistic driving simulations which allow observing human subjects in simulation experiments.

To assess the safety of the network, surrogate safety indices or measures must be used to approximate network safety. Safety indicators can measure network and vehicle attributes to assess the probability of collisions throughout the network. Research by Bai and Li (2006) showed that rear-end collisions are some of the most common types of work zone collisions. Traffic statistics collected have shown that rear-end collisions occur more frequently in work zones then in nonwork zones (Rouphail et al. 1988; Wang et al. 1996; Khattak et al. 2002). Therefore, this connected vehicle research will measure improved TTC values throughout the duration of the simulation for rear-end situations. Golob et al. (2004) found changes in mean volume and mean speed have noticeable effects on safety. Migletz et al. (1999) research also concludes there is a connection between changes in speed and collision probability.

There is a lack of research focusing on the real-world technological limitations of wireless connected vehicle information sharing, where each vehicle has a predetermined communication range. Other studies have used a global cost table that all vehicles can access to compute their optimal route, without taking into account the technical feasibility of real-world implementation. It is hypothesized that as the market penetration of connected vehicles increases, they will be able to communicate at further distances by forming larger ad-hoc networks with greater contiguous communication coverage. Studies which contain an element of dynamic route guidance are vague as to the specifics of their guidance algorithm. This paper will propose a decaying average travel time dynamic route guidance algorithm which exhibits weighted information decay, elaborated on in subsequent sections. The presence of work zones will also factor into the dynamic route guidance algorithm, with connected vehicles attempting to avoid work zones routes to their destination. The effect of various market penetrations of connected vehicles, with their accompanying applications, on traffic safety, measured through the improved time to collision surrogate safety measure, is studied on a network with work zones present.

Proposed Method

A control simulation of a network with a work zone and no connected vehicles will be compared to a network with a work zone present and varying market penetrations of connected vehicles to gauge the effects on the improved critical TTC values. Market penetrations of 20, 40, 60, 80, and 100% connected vehicles will be simulated to determine their effect on the safety of the network.

The vehicles simulated in the research reported in this paper are one of two types [(1) connected vehicles, and (2) nonconnected vehicles]. Connected vehicles have the ability to exchange information with other connected vehicles within a predetermined range and reroute using dynamic route guidance. Nonconnected vehicles do not have the ability to communicate or exchange information with any vehicles and always take the shortest path by distance to their destination, calculated at the beginning of their trip. A software plugin, written in the C programming language, was used in conjunction with the *Paramics*' API to implement the work zone, connected vehicle system, and statistics collection. The plugin facilitates communication between vehicles; connected vehicles share travel time and work zone hazard notification. Connected vehicles use this shared information in their dynamic route guidance to navigate to their destination.

Assumptions

The assumptions are as follows:

- Connected vehicles always comply with dynamic route guidance decisions.
- All (i.e., 100%) of the wireless VTV communications are successful and transmit information with 0% noise. This assumption is made consciously to simplify research efforts and can be viewed as a means to validate a proof-of-concept. Further research is needed to ascertain the effect of noise and less-than-optimal wireless communication environments on connected vehicle applications, i.e., inclement weather and interference. Some research has already produced results stating that wireless communications between vehicles is realistically much lower than 100%. Future efforts in this field should consider these findings to increase the realism of the simulation (Bai and Krishnan 2006).
- Connected vehicles share information every second of the simulation with other in-range connected vehicles. The DSRC communication has the potential to communicate with a frequency of 10 Hz; however this high frequency is to aid in safety applications. For the research reported in this paper a frequency of 1 Hz was chosen, in part to lessen computational load.
- Connected vehicles are equipped with the equivalent of a global positioning system which allows connected vehicles to calculate their position with accuracy of less than a metre. Connected vehicles are equipped with a map of the entire network, where each link can store data to be used in dynamic route guidance.

Safety Assessment

The research reported in this paper endeavors to assess the impacts of VTV communication and the proposed dynamic route guidance on the safety of a network afflicted by a work zone. Improved time to collision ($TTC_{improved}$), Eq. (1), is used as a surrogate measure to approximate the safety of the network (Bachmann et al. 2010)

$$\text{TTC}_{\text{improved}} = \frac{d_{LF}}{v_F - v_L} \tag{1}$$

where d_{LF} = distance between the leading and following vehicle; v_F = velocity of the following vehicle; and v_L = velocity of the leading vehicle. The improved TTC is computed for a leading vehicle and following vehicle, with the potential incident being a rear-end collision. Improved TTC values calculated at less than a threshold value of 1.5 s (Van der Horst and Hogema 1994) are considered indicative of two vehicles exhibiting a high probability of colliding. It is acknowledged that many other surrogate safety measures can be utilized to study traffic safety; rear-end critical TTC instances were chosen as an approximate gauge of network safety because rear-end collision are one of the most common types of collisions, accounting for 30% of all collisions in the United States (Singh 2003). Microsimulators lack of collision modeling forces researchers to utilize less-than-ideal methods to evaluate safety, a surrogate safety measure was chosen which identifies potential for one of the most common collisions to approximate network safety. The focus of the research reported in this paper is not exclusively work zone safety, but also it examines the global network effects of rerouting vehicles away from work zones.

Vehicle-to-Vehicle Communication

The C plugin controls all of the connected vehicle functionality; information exchange, work zone hazard, and dynamic route guidance. In this model, connected vehicles share link travel time and work zone hazard information. Each connected vehicle has the ability to store information about the network and in particular, the time it takes to traverse a link from beginning to end and the location of work zones. Connected vehicles share data with other connected vehicles using VTV communication within a 1,000-m range. Connected vehicles use dedicated short-range communications technology, which has a maximum range of 1,000 m (Yin et al. 2004).

All data exchanged by connected vehicles is time stamped to ensure only the most current information is shared. Work zone hazard warnings shared between connected vehicles also include link location data. Once connected vehicles become aware of a work zone hazard through information shared through VTV communication, connected vehicles will use dynamic route guidance and the work zone hazard warning location data to reroute to links where work zone hazards are not present. In order to achieve this, a travel time penalty is applied to the value stored in the connected vehicle's link travel time array. This penalty is applied by multiplying the work zone link travel time by a scalar factor of 4, in the dynamic route guidance calculation. The travel time penalty is applied in the research reported in this paper to ensure connected vehicles reroute and traverse routes that bypass work zones.

Paramics networks are composed of links (roads), nodes (intersections), and zones (origin/destination of vehicles). Each connected vehicle has an indexed array corresponding to all of the links in the network. When a connected vehicle leaves its origin, all of the link travel times are null or uninitialized. After a connected vehicle has traversed a link it stores the elapsed travel time in the corresponding element of the array and timestamps the data to be shared with other connected vehicles.

Modeling Driver Behavior

The research reported in this paper also implements three different models for how driver behavior changes after work zone warnings are received. Previous studies have attempted to incorporate change in driver behavior when presented information in microsimulation (Dia and Panwai 2007), specifically by modifying driver awareness and aggressiveness; however they were ambiguous in quantifying how driver behavior deviated. This paper will implement three models for driver behavior modification in response to work zone warnings/information; increasing driver awareness and decreasing aggressiveness according to three discrete, multinomial distributions (Table 1).

On entering the network, vehicles are randomly assigned awareness and aggressiveness characteristics which influence driving behavior such as vehicle headway and gap acceptance for lane changes. The values for awareness and aggressiveness are quantified in *Paramics* as integer values from zero to nine, where higher integers indicate greater amounts of aggressiveness or awareness. A higher aggressiveness will yield shorter vehicles headways while higher awareness values produce safer driving behavior. The subsequent example demonstrates how driver behavior would

Table 1. Three Multinomial Distributions Modeling Change in Driver Behavior

Driver behavior change model			
Conservative, C	Moderate, M	Liberal, L	Probability
0	1	2	0.68
1	2	3	0.27
2	3	4	0.05

change after receiving a work zone warning. Using the moderate (M) model, if a driver has an awareness of 5 and an aggressiveness of 4 then there is a 68% probability their behavior values will change by 1, 27% probability of change by 2, and a 5% probability of change by 3, after the driver becomes aware of a work zone. If the change in behavior is determined to be 2 (27% probability), then driver awareness will increase from 5 to 7 and their aggressiveness will decrease from 4 to 2. Three multinomial distributions are considered to address the uncertainty in driver behavior when faced with information. If the majority of drivers do not change their behavior in the presence of information, the conservative (C) model represents this case, while the liberal (L) distribution is used in the simulation to represent substantial changes in driver behavior.

The probabilities selected for the multinomial distributions were influenced by neurophysiological research (Thorpe et al. 1996). While not explicitly related, such research is a valid source for modeling deviation in human behavior, and normal distributions accurately model deviation in behavior of populations. The neurophysiological experiments were conducted based on the subjects' response to visual stimuli, similar to how Connected Vehicle would interface with drivers in real-world implementation.

In the simulation experiments, driver behavior changes in discrete amounts; therefore the normal distributions consulted from research had to be transformed into a discrete, multinomial distribution, to satisfy the simulation constraints. The specific probabilities chosen for the multinomial distribution reflect the SDs of a normal distribution. One SD from the mean of a normal distribution encompasses 68% of the population. This SD is then applied to the multinomial distribution, but in a discrete manner to reflect how a driver's behavior will deviate by an amount that is analogous to the SDs of a normal distribution. This process of using a normal distribution's SD to represent the probabilities of the multinomial distribution is repeated for SDs of 2 and 3.

The multidisciplinary nature of a driver's response to real-time travel information was a significant challenge for the realistic modeling of driver's behavior in the research reported in this paper. To resolve this challenge, three models were used, which yield a spectrum of results for analysis, instead of a static conclusion where only one behavior model is considered. Future research in this area should strive to use more realistic simulations which can capture deviation in human behavior when presented with information during driving situations.

Driver distraction is an important topic when discussing VTV technologies, but is beyond the scope of the research reported in this paper. Microsimulators alone do not offer the fidelity necessary to model driver distraction; additional tools and methods must be integrated to consider distraction issues. Regardless, any intelligent transportation systems (ITS) technology, VTV or other, at some stage in development should consider the potential safety effects of driver distraction. It can be hypothesized that theoretically sound applications may be developed that seem to improve safety in simulations, but actually have the inverse effect when used by real drivers. Designing ITS information interfaces that do not exhaust a driver's cognitive abilities is an important matter to ensure the safety benefits afforded by technology are not negated because the driver is distracted.

Dynamic Route Guidance Using Decaying Average Travel Time

Upon recording a link travel time, connected vehicles share this information with other connected vehicles in range for use in dynamic route guidance. All connected vehicle data is time-stamped at creation to ensure the most current information is used. The units used in this paper are meters for distance and seconds for time. Travel time information decays with age, with older travel time information being compared to newer data and the difference in timestamps determining the weighting in the decaying average travel time (DATT) function, seen in Eq. (2)

$$\mathrm{DATT} = \frac{tt_{\mathrm{old}}[1.0 - (z \times w)] + tt_{\mathrm{new}}[1.0 + (z \times w)]}{2} \quad (2)$$

where w = integer truncate $[(ts_{\mathrm{new}} - ts_{\mathrm{old}})/i]$, and the weight decay factors; ts_{new} and ts_{old} = new and old link travel time timestamps, respectively; tt_{new} and tt_{old} = new and old link travel times, respectively; i is the time decay interval (s); and z = decay factor ($0.0 < z < 1.0$). The time decay interval (i) and weight decay factor (z) values were chosen from experimental trials to be 10 and 0.1, respectively. These values can conceivably vary depending on the network and simulation model.

The work zone penalty was determined through numerical analysis. The goal of the work zone penalty was to achieve a significant decrease of connected vehicles traveling through the work zone to mitigate congestion and increase safety. This was accomplished by applying a scalar travel time penalty to all links with work zones in the dynamic route guidance calculations. The analysis began with no work zone penalty and incrementing the penalty by 1 until the number of connected vehicles traversing the work zone was less than a congestion threshold. The congestion threshold was determined to be 10% of the total vehicle capacity of the work zone links.

Ten percent capacity was chosen as the threshold for the research reported in this paper, but this value can be changed depending on the needs of the traffic researchers. Strong evidence has been presented in previous sections that work zones have increased collision risk compared to areas absent of work zones. The threshold should be some fraction of the total capacity to avoid these unsafe circumstances, but to assert that there is a fixed, optimal number for all situations would be careless. Ten percent was chosen because it would significantly decrease the vehicle population on the work zone, and thus avoid many of the opportunities for dangerous driving situations. Zero percent was not chosen because work zones are still areas traffic can traverse, but they are dangerous if too many vehicles are present. The threshold can be greatly influenced by the environment in which the work zone is setup and perhaps vary according to the current flow of traffic. For example, the threshold may vary according to how many approximately equivalent alternate route exists that bypass the work zone. If many equivalent alternatives exist, as could be found in urban networks, the threshold may be low, but rural areas may not exhibit any valid detours, and thus the threshold would be high. Ten percent capacity is considered as a valid initial threshold and it is urged that future research better understands how much traffic is optimal to traverse a work zone.

The work zone is 1,160 m in length, with three lanes in both directions (six lanes total). The work zone eliminates one lane for vehicles to travel on, leaving two lanes in each direction for vehicles to traverse (4 lanes $\times$ 1,160 m $=$ 4,640 m total work zone length). Each vehicle in the simulation is 3.5 m in length and the mean headway between vehicles is 1.5 m. With an effective length of 5 m/vehicle, the total capacity of the work zone links is 928 vehicles. This total capacity was determined by (4,460 m)/(5 m/vehicle) $=$ 928 vehicles.

The lowest work zone penalty which achieved a connected vehicle population below the congestion threshold would be used for simulation experiments. The vehicle population was recorded halfway through the simulation experiments, 37.5 min, considered sufficient time for vehicles to populate the network to appropriate levels. A Connected Vehicle market penetration of 100% was used for the numerical analysis; 100% market penetration of Connected Vehicle ensured that all vehicles in the network would be routed using the dynamic route guidance, and therefore be subject to the work zone penalty.

As seen in the results of the numerical analysis (Table 2), the vehicle population is below the congestion threshold with a work zone penalty of 4, therefore a scalar work zone penalty of 4 will be used in the dynamic route guidance calculations during the simulation experiments.

To facilitate dynamic route guidance, travel times are used in a modified Dijkstra (1959) algorithm where link travel times replace edge weights and additional penalties can be applied for links with work zones. The shortest path by travel time is computed whenever a connected vehicle departs a link and has to choose between two or more possible exit links. In addition, average link travel times (ALTTs) are also estimated by all connected vehicles at a preset period, 10 s in the research reported in this paper, shown in Eqs. (3) and (4)

$$\mathrm{Test} = (t_{\mathrm{current}} - t_{\mathrm{start}}) + \frac{d_{\mathrm{link}} - d_{\mathrm{traveled}}}{\left(\frac{d_{\mathrm{traveled}}}{t_{\mathrm{current}} - t_{\mathrm{start}}}\right)} \quad (3)$$

$$\mathrm{ALTT} = \frac{\sum_{i=0}^{n} \mathrm{Test}_i}{n} \quad (4)$$

where test refers to the estimated link travel time; t_{current} = current simulation time; t_{start} = time when the vehicle entered the link; d_{link} = total length of the link; d_{traveled} = distance travelled on the link; and n = number of vehicles on the link.

The dynamic route guidance functionality reroutes vehicles along the shortest path by travel time using the array of travel times embedded in the connected vehicle. In practice, drivers will attempt to minimize their travel time to their destination. In a network with low demand, where all links exhibit free-flow travel, the shortest path through the network is the fastest. However, as a network experiences higher demands, certain links which were previously part of fastest route will become congested, leading to a new fastest route composed of links which are different than the shortest route. Connected vehicles share link travel times and use this information as input to their dynamic route guidance in an attempt to traverse routes which minimize travel time, attempting to bypass congested routes, such as links with work zones present. The dynamic route guidance employed by connected vehicles strives to account for the dynamic status of traffic in the network, providing connected vehicles with information that can be used to avoid congested links.

Table 2. Work Zone Travel Time Penalty Numerical Analysis

Work zone penalty	Work zone vehicle population
1	726
2	499
3	250
4	43

Simulation Test Bed and Case Study

The microsimulation software *Paramics* controls the overall simulation while a C plugin implements the connected vehicle functionality, work zone, and statistics. A portion of Toronto, Ontario, Canada, has been modeled in *Paramics* for simulation (Fig. 1).

For calibration purposes, changes to balance congestion and acceptable vehicle flow were made by adding additional advance green signal phases at specific intersections. Information from the Transportation Tomorrow Survey, a phone-based 5% random sampling of commuters in the greater Toronto–Hamilton area conducted every 5 years, was used to create the origin–destination matrices, which define how many vehicles enter and exit the network. The overall demand of origin–destination matrices had to be reduced by 35% to achieve appropriate traffic flow. These modifications are considered acceptable even though a detriment to replicating reality in simulation, as the purpose of the research reported in this paper is to ascertain the effectiveness of connected vehicles, not microsimulation calibration. Simulation trials ran for 1:15:00 simulation time, the first 15 min populating the network with vehicles as well as populating the link travel time arrays. For every 1 s of simulation time that elapses, TTC values are computed for all vehicles in the simulation. The total number of critical TTC values ($0\ \mathrm{s} < \mathrm{TTC} < 1.5\ \mathrm{s}$) are calculated, along with the total number of critical TTC values on work zone links. Links with work zones acquire a penalty in the dynamic route guidance algorithm, making it more likely that connected vehicles will divert to links without work zones present en route to their destination. Analysis of the total number of critical TTC provides a measure of the safety of the network, with a lower total number of critical TTC values indicating safer traffic conditions.

Connected vehicles become aware of a work zone when they are within 1,000 m of the work zone and store the information which can be shared with other connected vehicles in communication range. Multiple simulations with varying initial conditions were

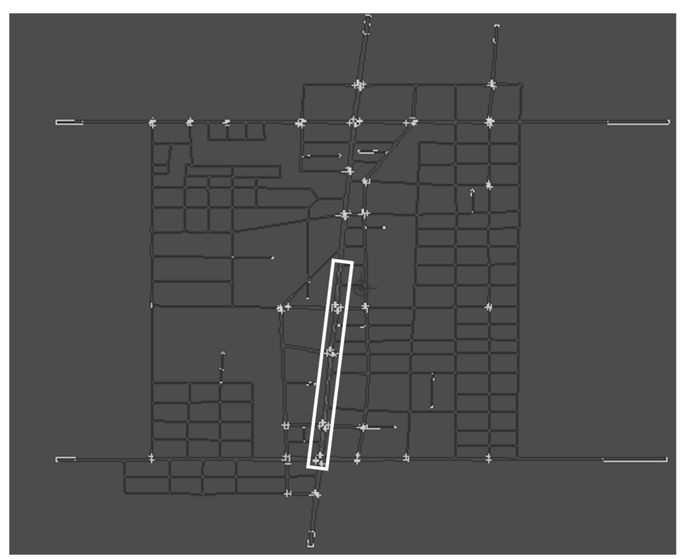

Fig. 1. Simulation model of a portion of Yonge and Sheppard, Toronto, Ontario, Canada, modeled in *Paramics*; work zone links are contained within the white box

executed and statistics were collected for analysis. Each driver behavior model (C, M, and L) was tested with varying levels of connected vehicle market penetration rate (MPR; 0, 20, 40, 60, 80, and 100%) with five different seed values. *Paramics* simulations begin with a seed value which introduces a level of randomness between simulations with different seeds influencing simulation events such as when vehicles are released into the network. Three behavior models each with six levels of connected vehicle market penetration and five different initial seeds yields a total of 90 simulations.

Analysis of Results

To assess the effects of connected vehicle technology on network safety, the nonparametric Mann–Whitney test is conducted to evaluate the subsequent null and alternate hypothesis. The variable of interest is the number of critical TTC values recorded during a simulation run. The variables m and n represent the number of trials. M_y is the median critical TTC values of a series of simulations with 0% market penetration of connected vehicles ($m = 5$). M_x is the median critical TTC values of a series of simulations with >0% market penetration of connected vehicles ($n = 5$)

$$\text{Hypothesis H0}, M_x \geq M_y \tag{5a}$$

$$\text{Hypothesis HA}, M_x < M_y \tag{5b}$$

Refer to Table 3 for statistical analysis of results. Recall that a p-value is used as criteria to reject the null hypothesis. Market penetrations of 20% for all behavior models leads to an increase in traffic safety (decrease in total number of critical TTC values) at 0.05 and 0.01 p-values. With a p-value of 0.01 for all behavior models at 20% connected vehicle market penetration, it is highly unlikely the null hypothesis has been mistakingly rejected, thus there is strong presumption to accept the alternative hypothesis, that the median number of critical TTC instances is less when 20% of vehicles are connected vehicles compared to 0%. For Behavior Model C, a market penetration of 40% connected vehicles leads to an increase in traffic safety at a p-value of 0.05, but does not at a p-value of 0.01. A p-value of 0.05 still indicates strong support to reject the null hypothesis that the median number of critical TTC instances is greater when 40% of vehicles are connected vehicles compared to 0% with Behavior Model C, but is not as strong as a p-value of 0.01. All market penetrations greater than 40% using the Behavior Model C do not lead to an increase in traffic safety.

Market penetrations of 20, 40, and 60% connected vehicles in accordance with the Behavior Model M lead to an increase in traffic safety at 0.05 and 0.01 p-values, indicating strong support to reject the null hypothesis and accept the alternative hypothesis. These p-values give strong support that market penetrations of 20–60% connected vehicles have a lower median number of critical TTC events than 0%. Market penetrations above 60% do not increase traffic safety compared to 0% market penetration. Behavior Model L show market penetrations from 0 to 100% connected vehicles lead to an increase in traffic safety. This result should be accepted with caution and understood within the context of the simulation, as the Behavior Model L signifies that all drivers who become aware of a work zone will substantially change their driving behavior (decrease aggressiveness/increase awareness), implying that any connected vehicles receiving information about a work zone will significantly change their behavior and no driver would ignore the warning message. It is highly unlikely that under any circumstances, especially a new technology such as connected vehicle, any system will ever attain 100% compliance from its users, with research finding many factors influencing driver compliance (Djavadian et al. 2014). The results of all three models can be observed in Table 3 to better grasp their effect on network safety.

The results presented in Fig. 2 can be analyzed in tandem with research conducted by the World Research Institute (WRI) Center for Sustainable Transport, EMBARQ (EMBARQ 2012). The EMBARQ compiled statistics collected by the Federal Highway Administration comparing the relationship between vehicle fatalities and average daily distance traveled by vehicles.

The EMBARQ found that the further, on average, daily distance a vehicle travels, the more likely a vehicle fatality will occur (EMBARQ 2012). While this paper's focus is on connected vehicles and work zones and not vehicle fatalities, these EMBARQ results concerning vehicle fatalities are related to traffic safety. As such the general trend that can be inferred from EMBARQ's analysis is that the further a vehicle travels, the more opportunities for a vehicle to be involved in an accident and potentially cause fatalities. Since a traffic accident must precede a fatality, this comparison is justified.

Table 3. Results of Mann–Whitney U Test for the Effects of Connected Vehicles on Network Safety

Connected vehicle MPR (%)	Behavior model[a]	Mann–Whitney test statistic, U	$p = .05$, $U <= 5$	$p = 0.01$, $U <= 2$	Average critical TTC count	Change (%) in average critical TTC count from control; CV 0%
0	—	—	—	—	7,153	—
20	C	0	Pass	Pass	6,397.6	−10.6
40	C	4	Pass	Fail	6,753.8	−5.6
60	C	25	Fail	Fail	8,109	+13.3
80	C	25	Fail	Fail	9,364.4	+30.9
100	C	25	Fail	Fail	12,212.4	+70.7
20	M	0	Pass	Pass	6,186	−13.6
40	M	0	Pass	Pass	6,145.4	−14.1
60	M	0	Pass	Pass	6,436.2	−10.1
80	M	17	Fail	Fail	7,203.2	+0.7
100	M	25	Fail	Fail	7,966.4	+11.3
20	L	0	Pass	Pass	5,985.8	−16.4
40	L	0	Pass	Pass	5,578	−22.1
60	L	0	Pass	Pass	5,541	−22.6
80	L	0	Pass	Pass	5,928	−17.2
100	L	0	Pass	Pass	5,830.8	−18.5

[a]As per Table 1.

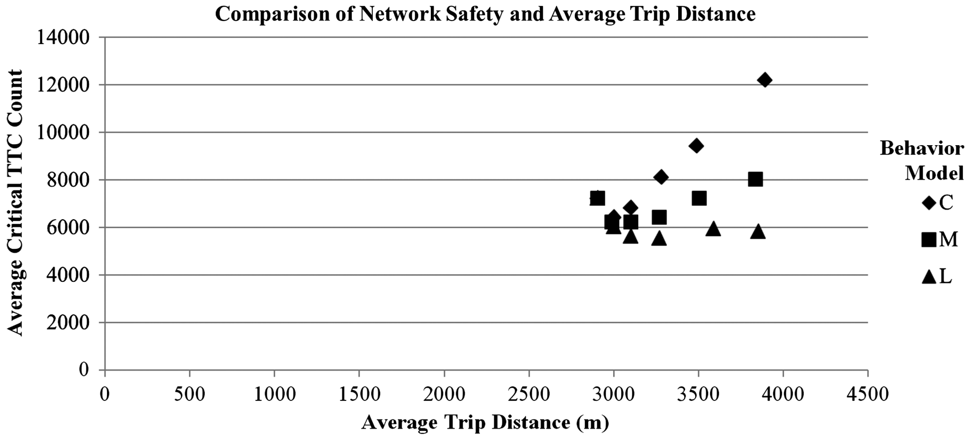

Fig. 2. Comparison of average trip distance and network safety

If any event has a nonzero probability of occurring in a trial, the more trials performed, the more opportunities for the event to occur. In a transportation context, the more units of distance a vehicle travels, the more opportunities the vehicle has to be involved in a situation where a critical TTC value occurs.

This conclusion is represented in the results from this paper, with the general trend that simulations with higher average vehicle trip distances, produced by higher market penetrations of connected vehicles, produces higher numbers of critical TTC values, but this trend is greatly influenced by the behavior model used [Figs. 3(a–c)]. Computing a correlation coefficient, R^2, between two variables is a measure of the degree to which two variables change in relation to each other. A positive correlation indicates that as one variable increases, so does the other, a negative correlation

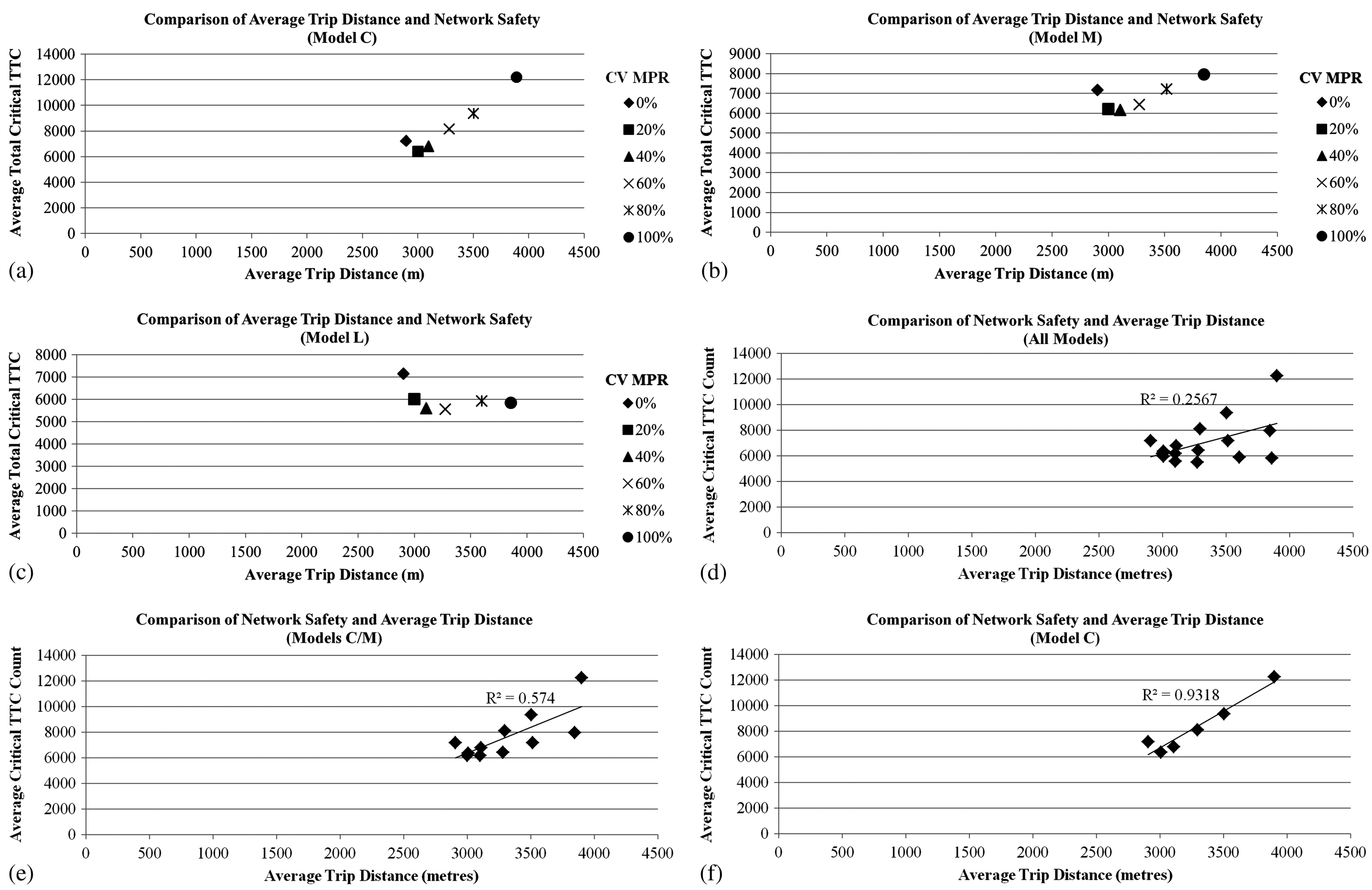

Fig. 3. (a) Comparison of average trip distance, market penetration, and network safety using Behavior Model C; (b) comparison of average trip distance, market penetration, and network safety using Behavior Model M; (c) comparison of average trip distance, market penetration, and network safety using Behavior Model L; (d) comparison of average trip distance and network safety using Behavior Models C, M, and L; (e) comparison of average trip distance and network safety using Behavior Models C and M; (f) comparison of average trip distance and network safety using Behavior Model C

indicates as one variable increases, the other decreases. A correlation coefficient is a value between −1.0 and 1.0; a strong correlation has a coefficient close to 1.0, indicating a strong relationship between variables. When considering all behavior models, the positive correlation between increasing average trip distance and increasing critical TTC counts is weak [$R^2 = 0.2567$; Fig. 3(d)]. This weak correlation can be explained by the substantial deviation in driver behavior caused by the liberal and moderate models. If driver behavior deviates substantially towards safer driving, increased trip distance does not affect safety. If researchers remove the Behavior Model L, which is liberal in its assumption that drivers will significantly modify their behavior, the correlation between increasing trip distance and increasing critical TTC count becomes much stronger [$R^2 = 0.574$; Fig. 3(e)]. The positive correlation between increasing trip distance and increasing critical TTC counts is at its strongest ($R^2 = 0.9318$) when considering only Behavior Model C, as drivers are not significantly modifying their behavior and therefore not decreasing the critical TTC count, yet are exposed to more possible critical TTC events due to their further average trip distance [Fig. 3(f)]. Behavior Model C shows a stronger positive correlation between trip distance and safety than the results found by EMBARQ (2012), and it is prudent to consider Behavior Model C the most valid of the behavior models, as it is the most conservative in its assumptions.

For all behavior models, as the market penetration of connected vehicles increases, the average trip distance also increases (Table 4). This can be explained by the fact that connected vehicles take the fastest path to their destination, which may be different than the shortest path by distance. Connected vehicles reroute around the work zone, which is situated in the network such that it is included in the shortest path by distance from many origins to destinations. A higher market penetration of connected vehicles routes more vehicles to routes which are not the shortest path by distance to their destination. However with behavior models where connected vehicles always change their awareness and aggressiveness attributes after receiving information, the trend of further driving increasing the critical TTC count is countered by the overall safer driving. This can lead to seemingly inflated network safety with greater than average travel distances, which are reflective of behavior models where drivers significantly alter their behavior for safer driving. These models are suitable if connected vehicle technology achieves high rates of compliance, but research has shown this is not a trivial problem to solve (Djavadian et al. 2014).

Table 4. Average Trip Distance and Work Zone Safety

Connected vehicle MPR (%)	Behavior model[a]	Average trip distance (m)	Average work zone critical TTC count
0	—	2,906.42	1,529
20	C	3,005.92	778.8
40	C	3,104.06	484.8
60	C	3,292.6	310.2
80	C	3,500.3	194.2
100	C	3,900.58	194.4
20	M	3,000.12	825.8
40	M	3,103.24	476.6
60	M	3,278.86	307.2
80	M	3,517.06	194
100	M	3,847.8	130.6
20	L	3,003.66	826.2
40	L	3,102.6	496.4
60	L	3,273.24	269
80	L	3,600.8	165.4
100	L	3,856.7	106.6

[a]As per Table 1.

When Behavior Model C is used, comparing the increase in the connected vehicle market penetration from 0 to 20% yields a decrease in total critical TTC values, or an increase in traffic safety, yet the average trip distance increases [Fig. 3(a)]. This trend of higher market penetrations of connected vehicles increasing average trip distance, leading to an increase in the number of critical TTC values is not reflected in the change from 0 to 20% market penetration in Behavior Model C. However, for Behavior Model C, the dominating trend of higher average travel distances increasing the total number of critical TTC values begins to manifest as you increase from 20% to higher market penetrations [Fig. 3(a)]. The aim of rerouting vehicles away from links with work zones present is to avert the unsafe driving situations that often arise in work zones, such as abrupt lane changes or deviations in speed and acceleration. However, diverting traffic away from work zones, which are part of the shortest path by distance, to their destination means that vehicles are explicitly traveling further to their destination. The conclusion that has become apparent from the research reported in this paper and its results is that there is a balance in regards to optimizing safety between the benefits gained in rerouting vehicles away from work zones, and the detriments simultaneously produced by vehicles traveling further distances to their destination. Vehicles may be avoiding the hazardous scenario of traversing a work zone, but in rerouting they are now exposed to more potentially unsafe driving situations on their longer route by distance to their destination.

The number of critical TTC values occurring in the work zone decreased as the market penetration of connected vehicles increased, as shown in Table 4.

The decrease in critical TTC values on work zones as the market penetration of connected vehicles increases is a result of fewer vehicles traversing routes with works zones present. Connected vehicles apply a travel time penalty to links with work zones in their dynamic route guidance calculations, increasing the likelihood that they will traverse links to their destination that do not have work zones present. Fewer vehicles traveling on links with work zones creates fewer opportunities for critical TTC values to occur, increasing traffic safety in work zones. This increase in traffic safety on links with work zones, through a reduction of critical TTC values, is independent of the behavior model. This can be attributed to the fact that only nonconnected vehicles are likely to travel through the work zones, as they do not share traffic information and therefore do not modify their driving behavior. Nonconnected vehicle populations decrease linearly in all behavior models, which explains why the critical TTC counts on links with work zones decreases in a strong linear fashion.

This balance in terms of network safety between rerouting around work zones and an increase in distance traveled can be offset by drivers changing their behavior, which is accounted for by the three behavior models and reflected in their results. Comparing Behavior Model C to M, Behavior Model M exhibits significantly fewer critical TTC values at all market penetrations. If drivers change their behavior the increased potential for unsafe driving situations can be mitigated by safer driving. Subsequently, if drivers further modify their driving behavior to be safer, changing from Behavior Model M to L, this offset is even more influential in producing safer driving conditions. As previously mentioned, expecting drivers to significantly alter their driving behavior and comply with connected vehicle information to such a degree as Behavior Model L is naïve and should be taken with caution, but its potential effect on traffic safety is considerable. If effective and competent connected vehicle systems can be designed and distributed to drivers, the potential gains in traffic safety are considerable as previously shown in Table 3. Despite the obstacles of achieving driver compliance, and assuming the most conservative behavior model, where most drivers do not modify their behavior, the research reported in this paper can conclude a 20–40% market penetration of connected vehicles which are equipped to reroute, using a VTV shortest travel time, dynamic route guidance algorithm, to avoid work zones, can lead to a statistically significant increase in traffic safety, 5–10%. These safety benefits are lost at market penetrations higher than 40% as the increased opportunities for unsafe driving conditions due to larger average trip distances offsets the safety gained from rerouting away from work zones. This paper's findings are in accordance with previous research, which found network performance deteriorated above 50% market penetration of vehicles equipped with dynamic route guidance (Luk and Yang 2003).

Conclusion

The research reported in this paper attempts to understand the effect that deploying connected vehicle technology has on traffic safety in a network with work zones. Experiments were carried out in a microsimulation environment, *Paramics*, using the surrogate safety measure improved TTC to gauge network safety. Various market penetrations of connected vehicles were utilized along with three different behavior models to account for the uncertainty in drivers' compliance with connected vehicle information. Connected vehicles used VTV communication to share real-time link travel time and work zone warnings as input to a dynamic route guidance system. A relationship was found between the safety benefits of rerouting around work zones and the detriments of longer average trip distances, which decreased safety. The effect of decreased safety attributed to longer average trip distances could be strongly mitigated by considering behavior models where drivers significantly modify their behavior, but these models should be accepted with caution as it has not fully understood how likely drivers will respond to connected vehicle technologies. The most conservative behavior model with a connected vehicle market penetration of 20–40% was an optimal solution in improving network safety. This behavior model reroutes enough vehicles away from work zones to reduce the total number of critical TTC by 5–10% while not diminishing the safety gains through larger average trip distances.

Future research is needed to improve the accuracy of driver behavioral response to information as sharing traffic information is only useful if the driver is likely to use it. Although it was beyond the scope of this paper, mobility concerns should be incorporated into future research in this area as well. Even though average travel distances increased as the market penetration of connected vehicles increased, it is uncertain if average trip duration increased; this relationship needs to be investigated in future research. Other network safety measures should also be contemplated in further studies, as improved TTC is only one of many surrogate metrics to measure traffic safety. Expanding the scope and scale of the traffic network is also suggested, as the network modeled in this paper is only a subset of a much larger metropolitan area.

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