A MICROSIMULATION APPROACH ASSESSING THE IMPACT OF CONNECTED VEHICLE ON WORK ZONE TRAFFIC SAFETY

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Abstract

Safety in transportation systems is of paramount concern to society; many improvements have been made in recent decades and yet thousands of fatalities still occur annually. Work zones in particular are areas with increased safety risks in transit networks. Advances in electronics have now allowed engineers to merge powerful computing and communication technologies with modern automotive and vehicular technology, known as connected vehicle. Connected vehicle will allow vehicles to exchange data wirelessly with each other and infrastructure to improve safety, mobility and sustainability. This thesis presents a paper that focuses on evaluating the impact of connected vehicle on work zone traffic safety. A dynamic route guidance system based on decaying average-travel-time and shortest path routing was developed and tested in a microscopic traffic simulation environment to avoid routes with work zones. To account for the unpredictable behaviour and psychology of driver's response to information, three behaviour models, in the form of multinomial distributions, are proposed and studied in this research. The surrogate safety measure improved Time to Collision was used to gauge network safety at various market penetrations of connected vehicles. Results show that higher market penetrations of connected vehicles decrease network safety due to increased average travel distance, while the safest conditions, 5%-10% reduction in critical Time to Collision events, were observed at market penetrations of 20%-40% connected vehicle, with network safety strongly influenced by behaviour model.

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"If I have seen further it is by standing on the shoulders of giants."

-Isaac Newton, 1676

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This thesis consists of the following paper:

Paper I

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Co-Authorship

This thesis has been prepared in accordance with the regulations for a 'Sandwich' thesis format or as a compilation of papers stipulated by the Faculty of Graduate Studies at McMaster University and has been co-authored.

Chapter 2: Impact of Connected Vehicle on Work Zone Network Safety through Dynamic Route Guidance

The methodology, development, model formulation and solution of the model were completed by W. Genders with the assistance and consultation of Dr. S. Razavi. The paper was written by W. Genders and edited by Dr. S. Razavi & W. Genders.

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1 Thesis Summary

1.1 Introduction and Scope

Modern society relies heavily on automotive vehicles for the transport of persons, goods and services. Ensuring these transportation systems are efficient and safe is one of society's preeminent interests. Advances in technology have steadily been integrating computing technologies with automotive vehicles. In recent years the United States Department of Transportation's (USDOT) connected vehicle research program has focused on using wireless communication to improve automotive transportation (USDOT 2013). The connected vehicle program seeks to improve traffic safety, mobility and sustainability through wireless communication between vehicles and infrastructure.

The goal of this research is to explore the effects of connected vehicle technology on traffic safety, with focus given to networks with work zones present. Maintenance on transportation infrastructure often occurs while the infrastructure is still in use and therefore can present risks to both drivers and maintenance workers. Connected vehicle offers the ability to share information regarding work zones in an effort to mitigate risk to all parties involved.

This thesis proposes a dynamic route guidance system based on decaying average-travel-time. Connected vehicles share travel times and work zone locations wirelessly with other connected vehicle through vehicle-to-vehicle communication and use this information to avoid routes with work zones. Three behavior models are proposed to account for the uncertainty in how driver's behaviour will respond when presented with connected vehicle information.

The traffic microsimulator, Paramics, was used to test the proposed research, with a portion of Toronto, Ontario, Canada modelled for testing. A C plugin was developed implementing the connected vehicle functionality in Paramics.

1.2 Background

1.2.1 V2V Applications

Connected vehicles share traffic information wirelessly; this thesis focuses on vehicle-to-vehicle (V2V) communication and its effects on work zones and safety. It is anticipated that widespread adoption of V2V communication can significantly improve safety on roads (USGAO 2013). V2V communication allows for the creation of vehicle ad-hoc networks to disseminate information across large distances (Hartenstein and Laberteaux 2008). Significant research on applications using V2V communication has already been published; a few example applications being studied are data routing protocols (Bilal et al. 2013) (Sharef et al. 2013), collision warnings (Cho et al. 2009) (Xu et al. 2011) and dynamic route guidance (Chen et al. 2010) (Khosroshahi et al. 2011).

This thesis models V2V as dedicated short-range communication with a range of 1000 m, the same technology being investigated by the United States government (NHTSA 2014). In this study, connected vehicles share work zone location along with travel times in an attempt to route away from unsafe and congested areas of the network, such as work zones.

1.2.2 Driver Behaviour

With connected vehicle research ongoing, uncertainty still exists regarding how drivers will react to information shared between vehicles. It is anticipated that connected vehicle and its applications will benefit transportation, i.e. increase safety and improve flow/mobility. However, special attention must be given to creating connected vehicle applications that driver's will be comfortable interacting with. A potential future can be imagined where connected vehicle systems are theoretically valid and perform well in simulations and controlled testing, yet perform poorly when implemented for society at large; it is paramount that researchers consider the behavioural and psychological aspects when designing these technologies. Some research efforts have already been made in this area including but not limited to, information filtering and its effect on protecting the driver's cognitive resources (Ye et al. 2013); potential interference effects of non-critical and critical warnings producing a bottleneck in human information processing (Ward et al. 2013); driver's behavioural adaptation to a forward collision warning system (Bueno et al. 2014) and driver behaviour changes in the presence of an intelligent speed adaptation system (Spyropoulou et al. 2014).

To account for the unpredictable human element of driver's response to information, three behaviour models, in the form of discrete multinomial distributions, are proposed in this thesis. These distributions govern how a driver's behaviour, modelled in the simulation as integers representing aggressiveness and awareness, will deviate after receiving connected vehicle information.

1.2.3 Work Zones

Research has shown that traffic conditions with work zones have higher crash rates compared to the same network without a work zone (Pal and Sinha 1996) (Khattak et al. 2002). Crash frequency in work zones was also affected by lane closures & construction intensity (Pal and Sinha 1996) (Venugopal and Tarko 2000) along with traffic conditions and driver behaviour (Daniel et al. 2000) (Harb et al. 2008). With work zones negatively affecting traffic safety, connected vehicle offers the opportunity to offset the detrimental effects of work zones by disseminating work zone warning messages. Instead of relying on conventional roadside signs, drivers would be given wireless warnings to become aware of work zones well in advance and have the opportunity to reroute. If vehicles can avoid traversing work zones, then the potential for unsafe traffic conditions on work zones can be significantly diminished.

This thesis proposes a dynamic route guidance system based on decaying average-travel-time which reroutes vehicles to avoid work zones. Connected vehicles share work zone locations along with travel times. New information is weighted higher in dynamic route guidance calculations, with data decaying in weight over time.

1.3 Summary of Papers

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

Work zones in traffic networks present safety risks to both drivers and construction workers. This paper introduces a work zone warning and dynamic route guidance system based on decaying average-travel-time using vehicle-to-vehicle communication. Three driver behaviour models are proposed to account for uncertainty in driver response to shared information. This system was applied in the microscopic traffic simulator Paramics, to a modelled network of Toronto, Ontario, Canada. The results showed that at low market penetrations of connected vehicles, an increase in safety was achieved; as market penetration increase, traffic safety decreased.

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

By Wade Genders, S. Razavi

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 this research 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 this study uses vehicle-to-vehicle communication to share information about work zone links and link travel times. Vehicles which receive work zone information will also modify their driving behaviour by increasing awareness and decreasing aggressiveness. This paper also proposes a decaying average-travel-time dynamic route guidance algorithm which exhibits weighted information decay. The traffic microsimulation software Paramics 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 is used to assess the safety of the network. Various market penetrations of connected vehicles were utilized along with three different behaviour models to account for the uncertainty in driver's response to connected vehicle information. The results show that network safety is strongly correlated with the behaviour 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 this research 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.

Keywords: Connected Vehicle; Vehicle-to-Vehicle (V2V) Communication; Work Zone; Safety; Dynamic Route Guidance; Decaying Weighted Average; Microsimulation.

2.1 Introduction

Connected vehicle is a United States Department of Transportation 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; this research aims to determine the effect of these applications on network safety. Vehicle-to-Vehicle (V2V) 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 (Institute of Transportation Engineers 1992). 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 aforementioned 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 via a surrogate device, often a smartphone, in the form of 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, humidity). Another difference is that connected vehicles can function without the support of a large infrastructure, establishing V2V, 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 will not function. However, having access to a large network infrastructure has benefits, as intense computation can be offloaded to the network and then transmitted back to the clients. Connected vehicle has been also designed to interface with a large, independent infrastructure, in the form of Vehicle-to-Infrastructure (V2I) communication.

This research 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 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 V2V and traffic safety (Azimi et al. 2011) (Xu at el. 2011) (Sepulcre & Gozalvez 2012) dynamic route guidance (Chen et al. 2010) (Khosroshahi et al. 2011), and other research has studied work zones (Ha & Nemeth 1995) (Pal & Sinha 1996) (Khattak et al. 2002). However, there exists a gap in using the specific technological characteristics of connected vehicle (V2V communication) in conjunction with dynamic route guidance and work zones. Previous studies have not integrated dynamic route guidance, V2V communication and work zones together. This research combines all of these elements in microsimulation and examines the effects on traffic safety.

The objective of this research is to assess the impact of connected vehicle technologies, specifically V2V 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 V2V communication. A custom C plugin in conjunction with the Paramics' Application Programming Interface (API) was developed to implement the connected vehicle applications and V2V 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. This research ventures to understand how traffic safety is affected by the use of a connected vehicle system in the presence of a work zone.

2.2 Literature Review

Connected vehicle technology has the potential to improve traffic safety, mobility and environmental impacts. The Transportation Research Board (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 V2V-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 V2V communication. Vehicles that become notified of incidents increase their awareness and decrease their aggressiveness. Kattan et al. found an overall improvement in network performance, with a decreased collision probability and decrease in path travel time for V2V and non-V2V 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, one set of vehicles were considered uninformed and did not have access to real time information regarding network conditions. The second type of vehicles had their cost-to-destination tables updated every 5 minutes 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 earlier 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 (ISWS). 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 ISWS 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 inter-driver 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. It should be noted that 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 (DSRC) vehicle-to-infrastructure (V2I)/V2V 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 via a roadside visual cue if they were exceeding the speed limit in the work zone. The outcome of this research 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 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 (VMS) are large digital displays placed strategically beside roadways presenting drivers with brief traffic information, such as an upcoming work zone or expected delays. VMS are the predominant method of communicating information to drivers and can be autonomous/embedded systems, receiving no input, or connected to a traffic control centre. Chatterjee & Mcdonald (2004) analyzed the results from 9 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% - 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 - 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 exists 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 indexes 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 non-work 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. Davis et al. (2002) and Kockelman et al. (2007) research also concludes there is a connection between changes in speed and collision probability.

There exists a lack of research focusing on the real world technological limitations of wireless connected vehicle information sharing, where each vehicle has a pre-determined 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 via the improved Time to Collision surrogate safety measure, is studied on a network with work zones present.

2.3 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% & 100% connected vehicle will be simulated to determine their effect on network safety.

The vehicles simulated in this research are one of two types, connected vehicles or non-connected vehicles. Connected vehicles have the ability to exchange information with other connected vehicles within a predetermined range and reroute using dynamic route guidance. Non-connected 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.

2.3.1 Assumptions

- Connected vehicles always comply with dynamic route guidance decisions.
- 100% of wireless V2V communications are successful and transmit information with 0% noise. It should be noted that 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 necessary 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%; the specific probability of successful communication is dependent on the transmission environment. Higher numbers of vehicles transmitting will increase interference and decrease successful communication probability. Relative position of transmitter/receiver along with the physical geometry of the communication environment can also significantly influence communication. For example, in dense, urban centres with large buildings, vehicles approaching an intersection with perpendicular trajectories will likely not be able to communication, as the wireless signals will not penetrate the buildings. However, in rural areas, successful communication probabilities may be close to 100%, due to lower

populations of connected vehicles and few obstacles to obstruct wireless signals. Future efforts in this field should consider these findings to increase the realism of the simulation (Bai & Krishnan 2006).

- Connected vehicles share information every second of the simulation with other in-range connected vehicles. DSRC communication has the potential to communicate with a frequency of 10 Hz; however this high frequency is to aid in safety applications. For this research 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 them 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.
- The safety of the network will be assessed by evaluating potential situations for rear-end collisions. Rear-end collisions are chosen because they are one of the most common forms of collision in work zones, and increase in frequency when compared to roadways not undergoing construction (Rouphail et al. 1988) (Wang et al. 1996) (Khattak et al. 2002).

2.3.2 Safety Assessment

This research endeavours to assess the impacts of V2V communication and the proposed dynamic route guidance on the safety of a network afflicted by a work zone. Improved Time to Collision (Equation 1) is used as a surrogate measure to approximate the safety of the network (Bachmann et al. 2010).

$$\mathrm{TTC}_{improved} = \frac{\mathrm{d}_{LF}}{V_{follow} - V_{leading}} \tag{1}$$

Where

$V_{leading}$: velocity of leading vehicle

V_{follow}: velocity of following vehicle

d_{LF}: distance between leading and following 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 seconds (Van der Horst & Hogema 1994) are considered indicative of two vehicles exhibiting a high probability of colliding. This research acknowledges 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 modelling forces researchers to utilize less than ideal methods to evaluate safety, this research chose a surrogate safety measure which identifies potential for one of the most common collisions to approximate network safety. It should be noted and clarified that the focus of this research is not exclusively work zone safety, but also it examines the global network effects of rerouting vehicles away from work zones.

2.3.3 V2V 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 V2V communication within a 1000 metre range (Figure 1). Connected vehicles use Dedicated Short Range Communications (DSRC) technology, which has a maximum range of 1000 metres (Yin et al. 2004).

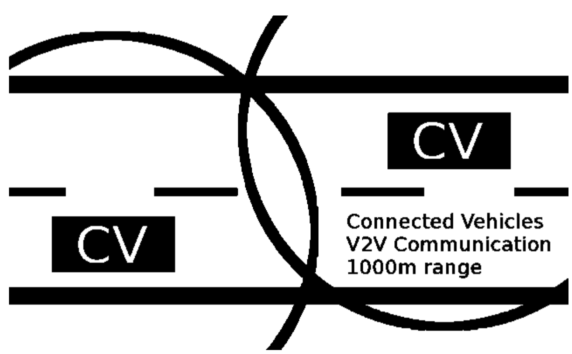

Figure 1: Two connected vehicles with overlapping V2V communication ranges (1000 metres), enabling V2V communication/data exchange.

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 via V2V 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 by the research team 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 (Figure 2 and Figure 3). In Figure 3, the connected vehicle has traversed link 5 and stored data in the corresponding element of the array.

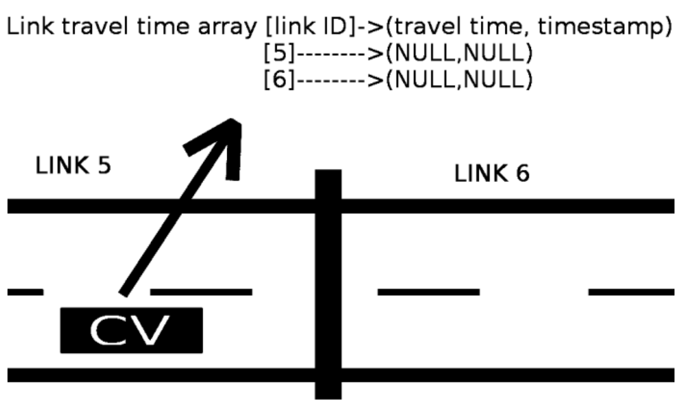

Figure 2: A connected vehicle without any information in its link travel time array.

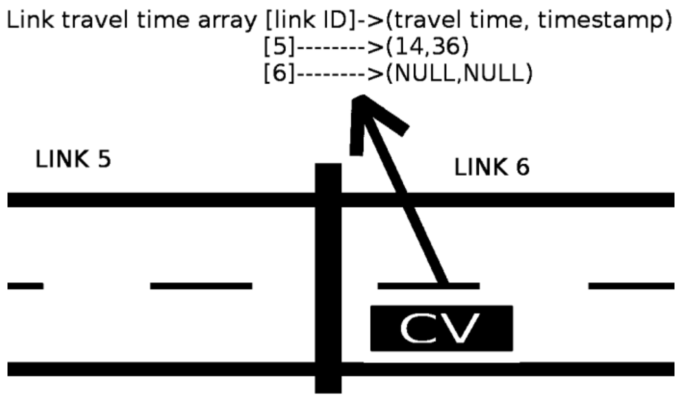

Figure 3: After a connected vehicle has traversed a link.

2.3.4 Modelling Driver Behaviour

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

Table 1: 3 Multinomial distributions describing change in driver behaviour.

Driver Behaviour Change Model			
Conservative(C)	Moderate(M)	Liberal(L)	Probability
0	1	2	0.68
1	2	3	0.27
2	3	4	0.05

On entering the network, vehicles are randomly assigned awareness and aggressiveness characteristics which influence driving behaviour such as vehicle headway and gap acceptance for lane changes. The values for awareness and aggressiveness are quantified in Paramics as integer values from 0 – 9, 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 behaviour. The following example demonstrates how a driver's behaviour would 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 behaviour 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 behaviour is determined to be 2 (27% probability), then the driver's 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's behaviour when faced with information. If the majority of driver's do not change their behaviour 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 the driver's behaviour.

The probabilities selected for the multinomial distributions were influenced by neurophysiological research (Thorpe et al. 1996). While not explicitly related, this research is a valid source for modeling deviation in human behaviour, and found that normal distributions accurately model deviation in behaviour 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's behaviour changes in discrete amounts, therefore the normal distributions consulted from research were converted to a discrete, multinomial distribution, to satisfy the simulation constraints. The specific probabilities chosen for the multinomial distribution reflect the standard deviations of a normal distribution. 1 standard deviation from the mean of a normal distribution encompasses 68% of the population. This standard deviation is then applied to the multinomial distribution, but in a discrete manner to reflect how a driver's behaviour will deviate by an amount that is analogous to the standard deviations of a normal distribution. This process of using a normal distribution's standard deviation to represent the probabilities of the multinomial distribution is repeated for standard deviations of 2 and 3.

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

2.3.5 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. 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 function (Equation 2).

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

Where

$$w = \text{integer truncate}\left(\frac{ts_{new} - ts_{old}}{i}\right)$$

$$ts_{new}\text{: new time stamp}$$

$$ts_{old}\text{: old time stamp}$$

$$tt_{new}\text{: new travel time}$$

$$tt_{old}\text{: old travel time}$$

$$i\text{: time decay interval in seconds}$$

$$z\text{: decay factor } (0.0 < z < 1.0)$$

$$w\text{: decay weight factor}$$

$$\text{DATT: decaying average} - \text{travel} - \text{time}$$

The time decay interval (i) and weight 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. Specifically, the time decay interval and weight factor can vary according to how dynamic the network conditions are; urban networks change much more rapidly than rural networks due to higher vehicle populations. In a dense, downtown core a small time decay interval and large decay factor would better reflect the dynamic and variable state of traffic. In rural areas, the time decay interval may need to be larger and decay factor smaller, as network conditions will not change as often when compared to urban areas.

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 travelling 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 then began 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.

10% capacity was chosen as the threshold for this study, 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. This research chose 10% because it would significantly decrease the vehicle population on the work zone, and thus avoid many of the opportunities for dangerous driving situations. This research did not chose 0% 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. We consider 10% capacity as a valid initial threshold and urge future research to better understand how much traffic is optimal to traverse a work zone.

The work zone is 1160 metres in length, with 3 lanes in both directions (6 lanes total). The work zone eliminates 1 lane for vehicles to travel on, leaving 2 lanes in each direction for vehicles to traverse (4 lanes * 1160 m = 4 640 m total work zone length). Each vehicle in the simulation is

3.5 metres in length and the mean headway between vehicles is 1.5 metres. With an effective length of 5 metres per vehicle, the total capacity of the work zone links is 928 vehicles. This total capacity was determined by the following equation: (4460m)/5(m/veh) = 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 minutes, 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.

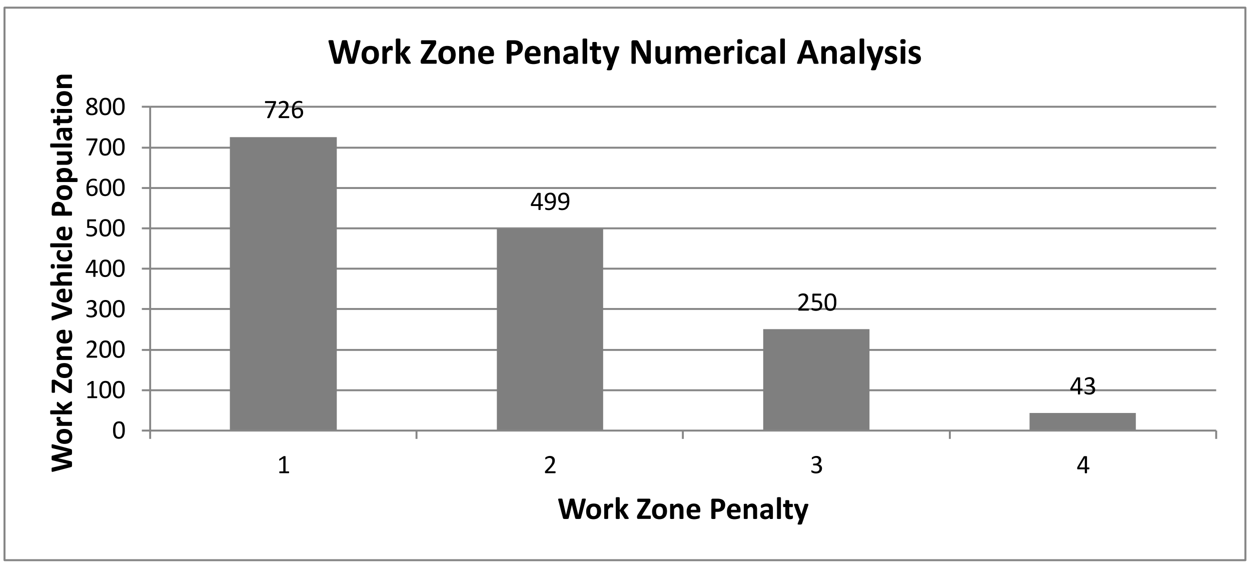

Figure 4: Work zone penalty numerical analysis, conducted at 100% market penetration of connected vehicle, work zone vehicle populations recorded halfway through simulation duration.

As seen in the results of the numerical analysis (Figure 4), 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's algorithm (Dijkstra 1959) where link travel times replace edge weights and additional penalties can be applied for links with work zones. Dijkstra’s algorithm was chosen because it adequately solves the problem of finding the shortest path through the network; it does not add any additional complexity or unnecessary computation. 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 are also estimated by all connected vehicles at a pre-set period, 10 seconds in this study (Equation 3& Equation 4).

$$\mathrm{T}est = (\mathrm{t}_{current} - \mathrm{t}_{start}) + \left(\frac{\frac{\mathrm{d}_{link} - \mathrm{d}_{travelled}}{\mathrm{d}_{travelled}}}{\mathrm{t}_{current} - \mathrm{t}_{start}}\right) \tag{3}$$

$$\mathrm{ALTT}(n) = \frac{\sum_{i=0}^{n} \mathrm{T}est_{(i)}}{n} \tag{4}$$

$\mathrm{d}_{travelled}$: total distance travelled on link

d_{link}: total length of link in metres

$\mathrm{t}_{current}$: current simulation time in seconds

t_{start}: time stamp when vehicle entered link

$\mathrm{T}est$: estimated link travel time

n: number of vehicles on link

$\mathrm{ALTT}(n)$: average link travel time for n 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 information that can be used to avoid congested links.

2.4 Simulation Test bed and Case Study

The microsimulation software Paramics controls the overall simulation while a C plugin implements the connected vehicle, work zone and statistics. A portion of Toronto, Ontario, Canada has been modeled in Paramics for simulation (Figure 5).

Figure 5: Simulation model of a portion of Yonge & Sheppard, Toronto, Ontario, Canada modelled in Paramics.

It should be noted that 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 this research is to ascertain the effectiveness of connected vehicle, not microsimulation calibration. Simulation trials ran for 1:15:00 simulation time, the first 15 minutes populating the network with vehicles as well as populating the link travel time arrays. For every second of simulation time that elapses, TTC values are computed for all vehicles in the simulation. The total number of critical TTC values ($0 \text{ s} < TTC < 1.5 \text{ s}$) 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 the DSRC read range from 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 executed and statistics were collected for analysis. Each driver behaviour model (C, M, L) was tested with varying levels of connected vehicle market penetration (0%, 20%, 40%, 60%, 80%, 100%) with 5 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 behaviour models each with 6 levels of connected vehicle market penetration and 5 different initial seeds yields a total of 90 simulations.

2.5 Analysis of Results

To assess the effects of connected vehicle technology on network safety, the non-parametric Mann-Whitney test is conducted to evaluate the following null and alternate hypothesis. The variable of interest is the number of critical TTC values recorded during a simulation run. The variables m & n represent the number of trials.

My is the median critical TTC values of a series of simulations with 0% market penetration of connected vehicles (m=5).

Mx is the median critical TTC values of a series of simulations with >0% market penetration of connected vehicles (n=5).

H0: Mx ≥ My

HA: Mx < My

Table 2: Results of Mann Whitney U test for the effects of connected vehicle on network safety.

CV (%)	Behaviour Model	Mann-Whitney Test Statistic(U)	P = .05 U<=5	P = 0.01 U<=2
20	C	0	Pass	Pass
40	C	4	Pass	Fail
60	C	25	Fail	Fail
80	C	25	Fail	Fail
100	C	25	Fail	Fail
20	M	0	Pass	Pass
40	M	0	Pass	Pass
60	M	0	Pass	Pass
80	M	17	Fail	Fail
100	M	25	Fail	Fail
20	L	0	Pass	Pass
40	L	0	Pass	Pass
60	L	0	Pass	Pass
80	L	0	Pass	Pass
100	L	0	Pass	Pass

Refer to Table 2 for statistical analysis of results. Recall that a p-value 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 we have mistakenly rejected the null hypothesis, 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 behaviour 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 following the M behavior model lead to an increase in traffic safety at 0.05 & 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 0-100% 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's compliance (Djavadian et. al 2014).All three models results can be observed in Figure 6 and Table 3 to better grasp their effect on network safety.

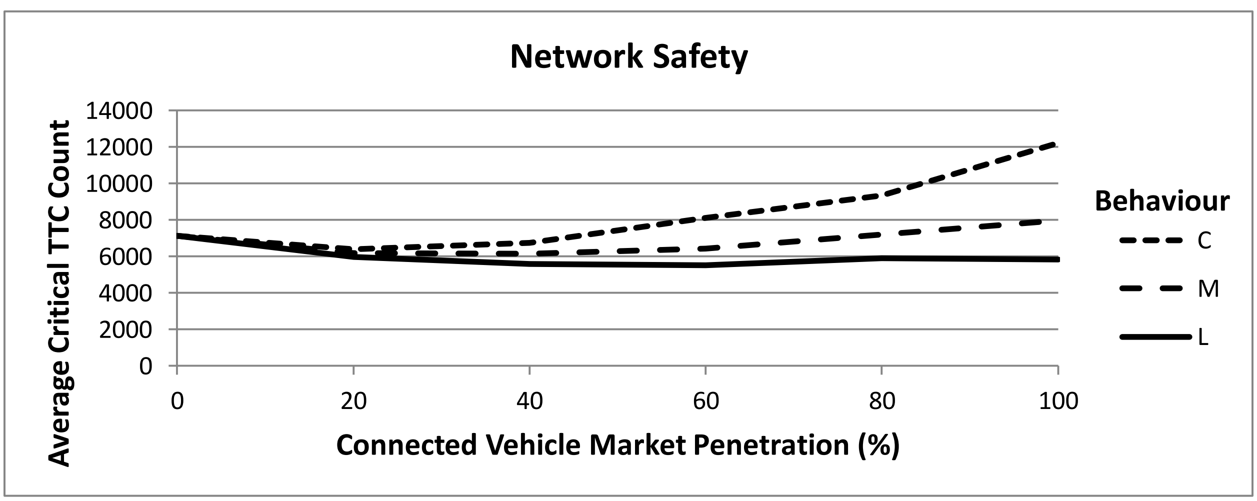

Figure 6: Effects of connected vehicle market penetration and behaviour model on network critical TTC count.

Table 3: Change in network critical TTC count for differing market penetrations and behaviour models.

CV (%)	Behaviour Model	Change(%) in critical TTC count from control(CV 0%)
20	C	-10.6
40	C	-5.6
60	C	+13.3
80	C	+30.9
100	C	+70.7
20	M	-13.6
40	M	-14.1
60	M	-10.1
80	M	+0.7
100	M	+11.3
20	L	-16.4
40	L	-22.1
60	L	-22.6
80	L	-17.2
100	L	-18.5

The results presented in (Figure 8) can be analyzed in tandem with research conducted by the WRI Centre for Sustainable Transport – EMBARQ (EMBARQ 2012). EMBARQ compiled statistics collected by the Federal Highway Administration comparing the relationship between vehicle fatalities and average daily distance travelled by vehicles, seen in Figure 7.

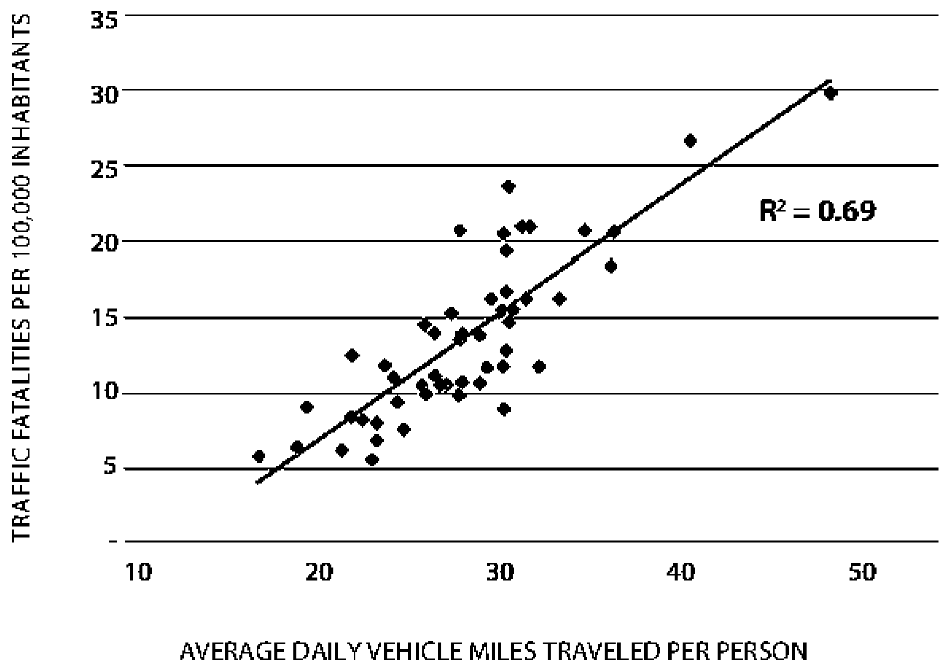

Figure 7: Comparison of average daily vehicle travel and traffic fatalities in urban areas, statistics compiled from FHWA 2008, analysis by EMBARQ ("The relationship between vehicle travel and traffic fatalities in United States urban areas" by EMBARQ, used under CC BY-NC 3.0/ image converted to black and white, selected from report "Our Approach to Health and Road Safety").

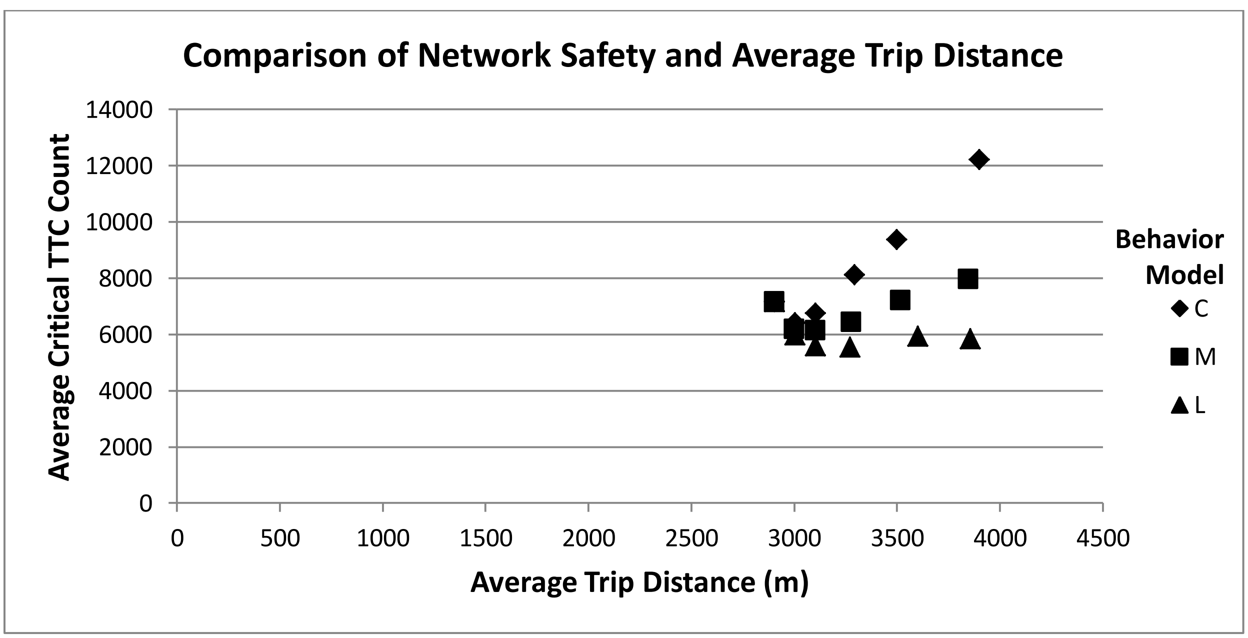

Figure 8: Effects of average trip distance and behaviour model on network safety.

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 vehicle 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.

If any event has a non-zero 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 behaviour model used (Figure 9, Figure 10, Figure 11). 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 indicates as one variable increases, the other decreases. A correlation coefficient is a value between 0.0 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 ($R^2 = 0.2567$) (Figure 12). This weak correlation can be explained by the substantial deviation in driver behavior caused by the liberal and moderate models. If driver's behavior deviates substantially towards safer driving, increased trip distance doesn't affect safety. If we remove the behavior model L, which is liberal in its assumption that driver's will significantly modify their behavior, the correlation between increasing trip distance and increasing critical TTC count becomes much stronger ($R^2 = 0.574$) (Figure 13). 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 (Figure 14). Model C shows a stronger positive correlation between trip distance and safety than the results found by EMBARQ (2014), and it is prudent to consider model C the most valid of the behaviour models, as it is the most conservative in its assumptions.

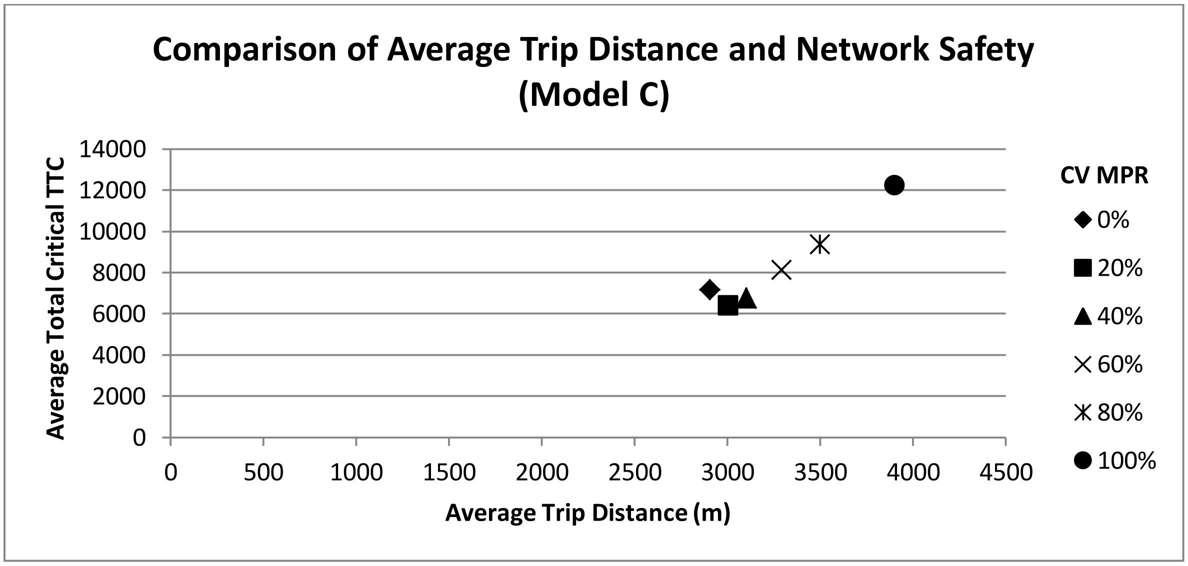

Figure 9: Comparison of average trip distance and network safety (Model C).

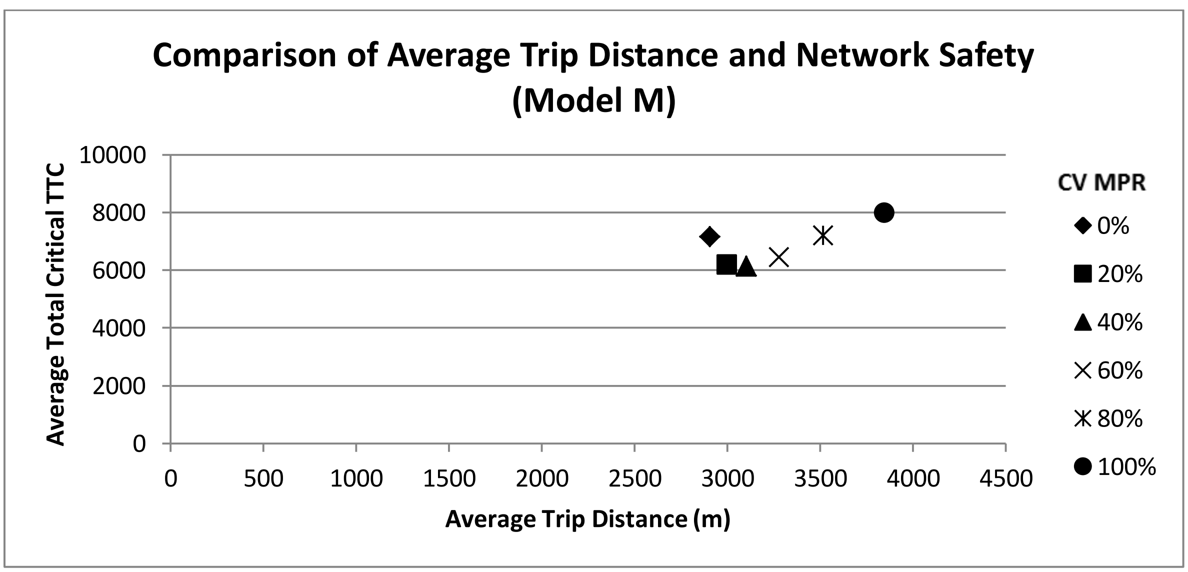

Figure 10: Comparison of average trip distance and network safety (Model M).

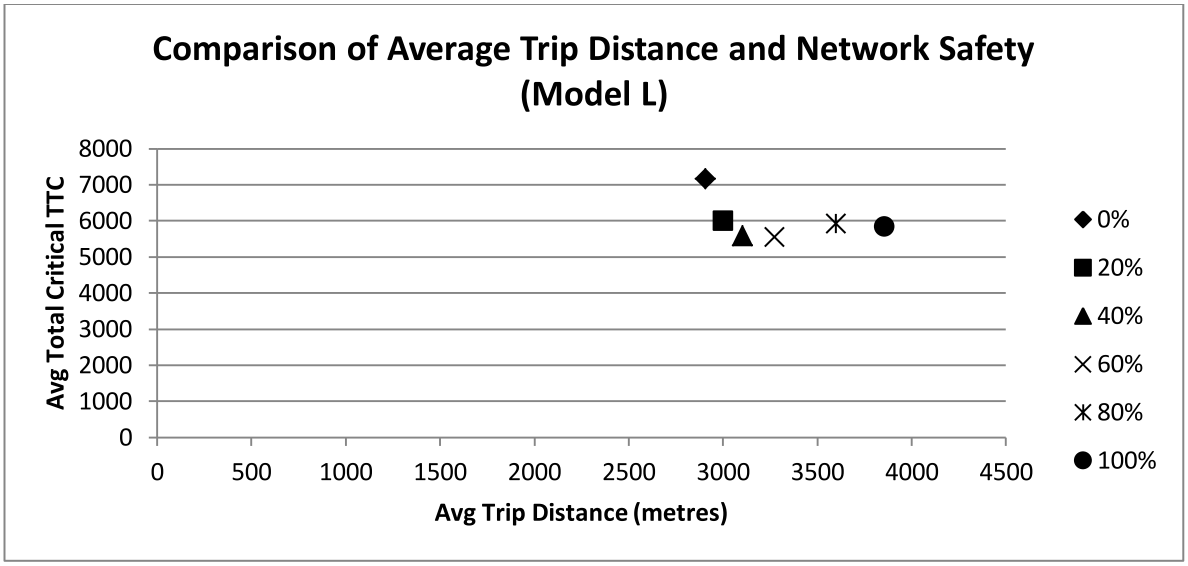

Figure 11: Comparison of average trip distance and network safety (Model L).

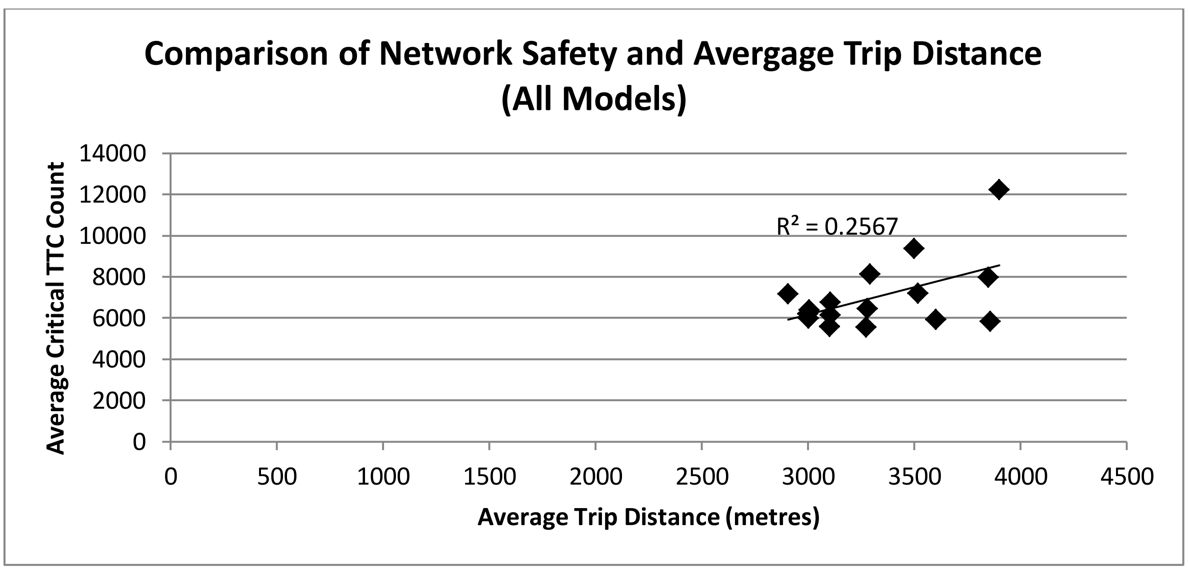

Figure 12: Comparison of network safety and average trip distance (All Models).

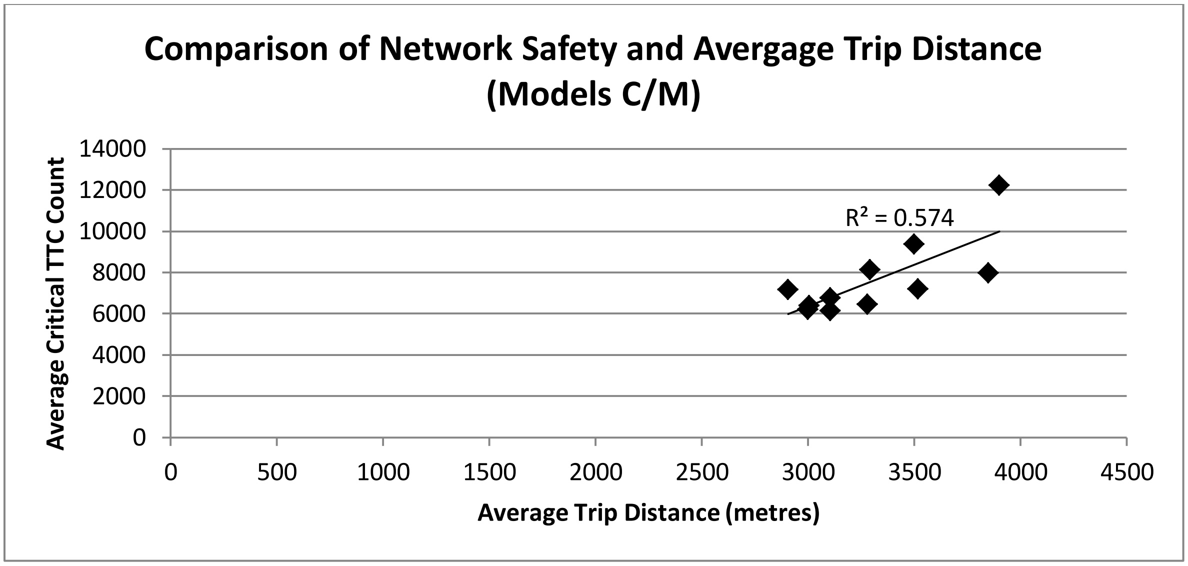

Figure 13: Comparison of network safety and average trip distance (Models C/M).

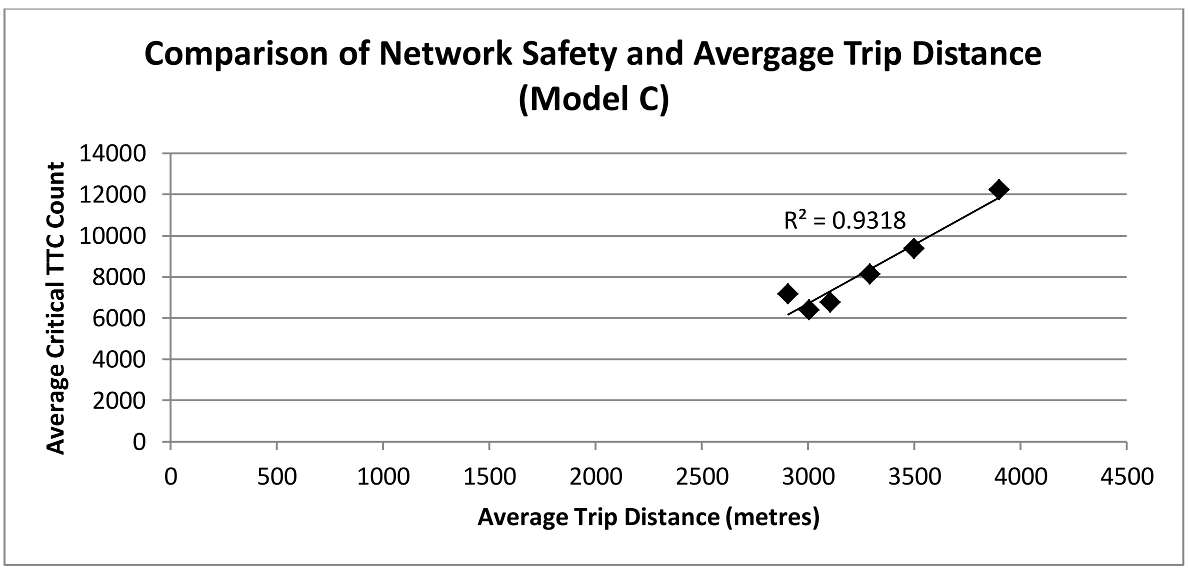

Figure 14: Comparison of network safety and average trip distance (Model C).

It should be noted that for all behaviour models, as the market penetration of connected vehicles increases, the average trip distance also increases (Figure 15). This can be explained by the fact that connected vehicles take the shortest path by travel time 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).

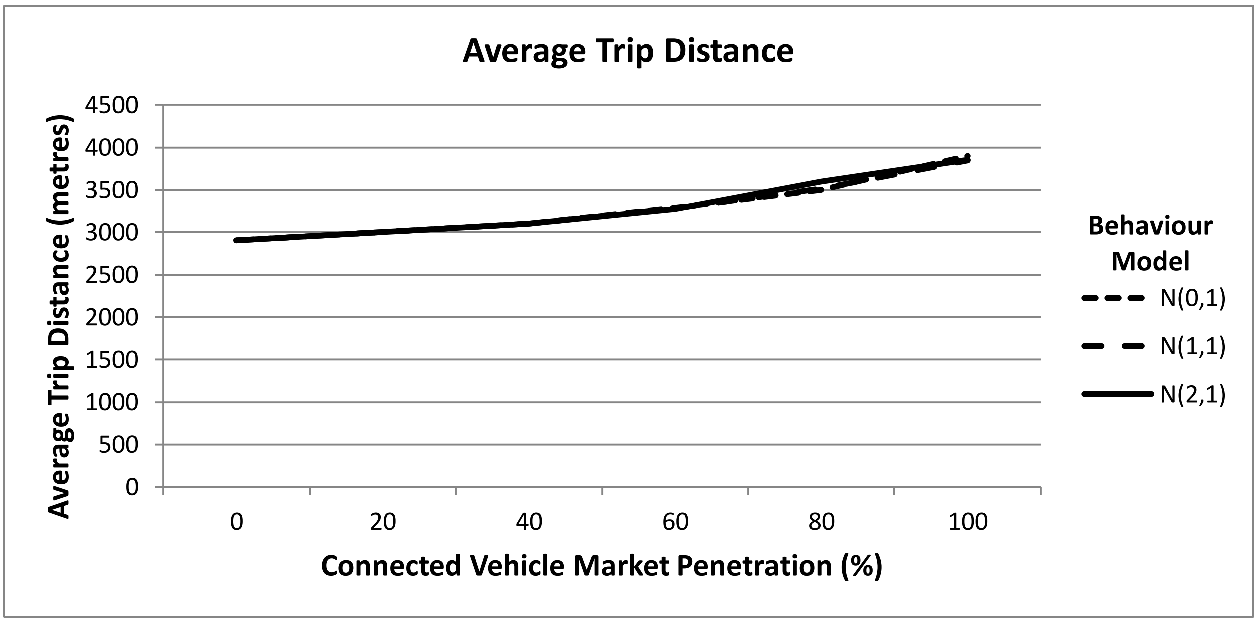

Figure 15: Comparison of average trip distance and connected vehicle market penetration.

When the C behaviour model 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 (Figure 9). 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 the C behaviour model. However, for the C behaviour model, 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 (Figure 9). 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 in the simulation network, to their destination means that vehicles are explicitly travelling further to their destination. The conclusion that has become apparent from this research and its results is that there exists 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 travelling 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, seen in Figure 16.

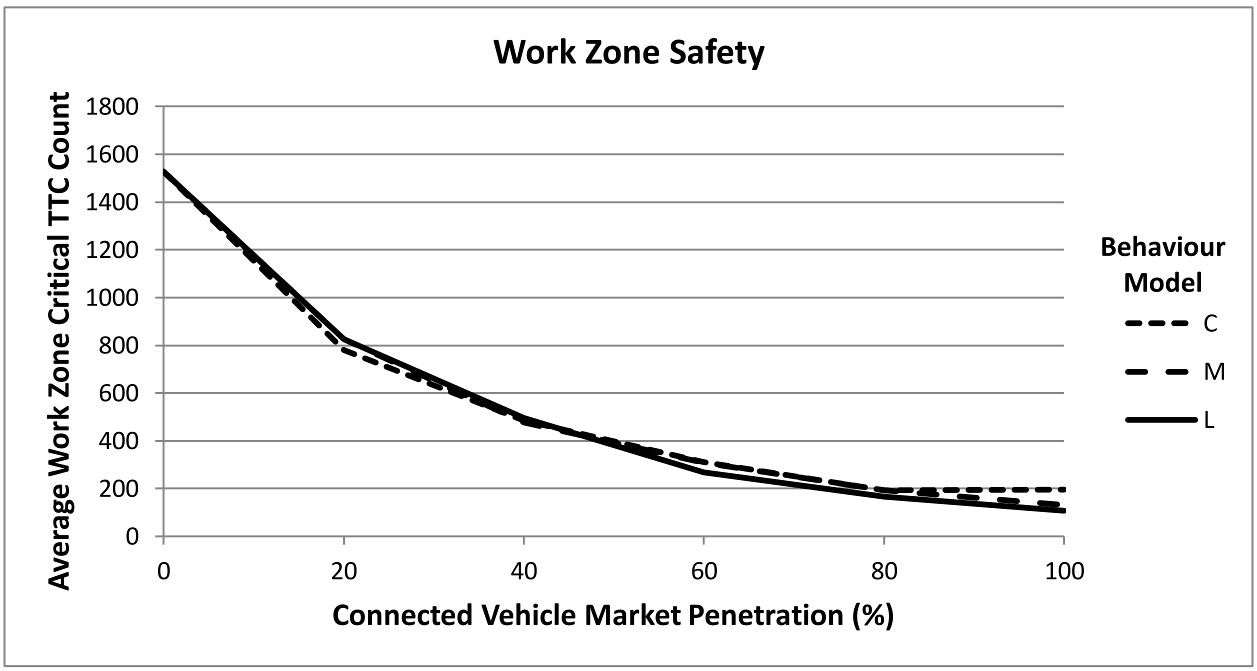

Figure 16: Effects of connected vehicle market penetration and behaviour model on work zone critical TTC count.

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 travelling 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 behaviour model used due to the fact that only non-connected vehicles are likely to travel through the work zones, as they do not share traffic information and therefore do not modify their driving behaviour. Non-connected vehicle populations decrease linearly in all behaviour 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 travelled can be offset by drivers' changing their behaviour, which is accounted for by the three behaviour models and reflected in their results. Comparing the C behaviour model to the M model, M exhibits significantly fewer critical TTC values at all market penetrations. Obviously, if drivers change their behaviour the increased potential for unsafe driving situations can be mitigated by safer driving. Subsequently, if drivers further modify their driving behaviour to be safer, from behaviour 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 behaviour and comply with connected vehicle information to such a degree as the L behaviour model 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 C behaviour model where most drivers do not modify their behaviour, this research can conclude a 20% - 40% market penetration of connected vehicles which are equipped to reroute, using a V2V 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).

2.6 Summary and Concluding Remarks

This research 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 V2V 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 found to be 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 drivers' 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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