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ENHANCING RESILIENCE OF TRAFFIC NETWORKS WITH CONNECTED VEHICLES

Ata M. Khan
Carleton University, Canada

Matthew Whelen
Carleton University, Canada

Naser Snobar
Carleton University and Morrison Hershfield, Canada

Omar Elsafdi
Carleton University, Canada

Brooke Jones
Carleton University, Canada

Patricia Arnold
Carleton University, Canada

ABSTRACT

Improving resilience of transportation infrastructure is a multifaceted subject. One of these addresses the traffic serving capability of the transportation system. As the profession progresses in finding ways to improve infrastructure resilience in physical terms, an associated thought process is underway to enhance the adaptive capacity in traffic networks with intelligent systems and advanced related methods in order to cope with shocks in the traffic environment caused by nature-induced or other events. This paper reports research in-progress on measures for enhancing the resilience of road traffic networks with applications of connected vehicles. The need for resilient road traffic networks is defined in order to reduce the risk of severe loss of capability to serve demand. Resilience is the ability to resist the loss of traffic-serving capability by using traffic (geometric) and control system design advances (i.e. the inherent resilience) and by dynamically activating capacity-enhancing measures (i.e. the dynamic resilience). There is a need to go beyond the adaptive traffic control of intersections by enhancing inherent plus dynamic resilience of the traffic system at a broader spatial scale of a corridor or a wide-area road network. Connected vehicle technology and associated methods that yield resiliency measures (i.e. adaptive capacity attributes) are described. Ideas are advanced on how to apply these resiliency measures in practice in order to address efficiency and other issues in urban transportation. Finally, concluding remarks are presented on the technical feasibility of implementing the research ideas presented in this paper.

Keywords: Resilience, traffic, intelligent transportation system, networks, connected vehicles, adaptive capacity

1. NEED FOR RESEARCH IN RESILIENCE OF TRAFFIC NETWORKS

Resilience is defined as the ability to resist the loss of traffic-serving capability owing to geometric and control system design (i.e. the inherent resilience) and by dynamically activating capacity-enhancing measures (i.e. the dynamic resilience). More than a decade ago, an initial step in this direction was taken in the form of adaptive traffic control of intersections. Its installations have progressed well around the world (Jagannathan and Khan 2001, Stevanovic 2010). Due to emerging new requirements, there is a need to go beyond this technology by enhancing inherent plus dynamic resilience of the traffic system at a broader spatial scale of a corridor or a wide-area road network. In an attempt to withstand predictive but very high imbalances of demand vs. capacity as well as stochastic severe traffic overloads and recover functionality at a tolerable level of performance within an acceptable time period. Considering that some links in such networks offer bimodal (i.e. private car/truck as well as public transit) service, opportunities as well as challenges increase.

Research products that integrate intelligent technology, predictive models, and decision aids for active traffic management are needed for enhancing "resilience of adaptive capacity" to overcome vulnerabilities of links or an entire route in the network. These can be implemented in active traffic management under unusual conditions that require adaptation within the driver-selected route as well in diversion routes that may be used for preventing severe congestion.

Although there are many facets of resilience of the urban transportation system, research underway at Carleton University will focus on improving resilience of adaptive capacity in traffic networks with intelligent systems and advanced methods. When such capability becomes available on a real-time basis for use in the best-suited traffic assignment (i.e. dynamic or system-optimal) and route guidance parts of active traffic management, they will serve an important function.

Some building blocks for research are available and additional items will be required. Also, there will be the need to integrate these within a systematic framework for maximum effectiveness. Examples of resilience measures developed at Carleton University include real time optimization of traffic signal timing transition (Qin and Khan 2012), control techniques for maintaining the existing vehicular capacity of the roadway infrastructure while improving travel time advantage of transit vehicles on shared use facilities (Mucsi and Khan 2011), dynamic metering of ramps in integrated freeway-arterial corridors and traffic adaptive high occupancy vehicle/toll lanes (Gryz et al 2007, Armstrong and Khan 2008).

2. STATE OF SCIENTIFIC KNOWLEDGE

The subject of inherent (also called static) and dynamic resilience of adaptive capacity in urban traffic networks is "new and developing." Although the benefits of adaptive traffic control were acknowledged over a decade ago, research in systems of higher capability and wider scope has been fragmented, and published sources are very scarce. However, there is a general recognition in the research community that enhanced knowledge of this subject is necessary for coping with predictive recurring major changes in traffic demand as well as stochastic non-recurring overloads of traffic. These random surges of traffic could be caused by incidents (e.g. traffic collisions), severe weather-related disruptions (some induced by long-term climate change), and many other nature-induced or man-made disruptions.

Specifically, the following observations are drawn from the literature regarding what has been done, what was found, and what needs to be done to advance knowledge in this subject.

2.1 Knowledge gaps

Following studies in New York and New Jersey urban areas, Nelson (2013) pointed out that there is an urgent need to improve our understanding of resilience in urban transportation. Tamvakis and Xenidis (2012) have found that resilience engineering, in spite of its rapid advances as a methodological approach, has not been adequately applied to transportation systems. They pointed out a lack of research in estimating system's resilience characteristics.

2.2 Resilience as a new focus on the city systems

According to a recent Editorial article, published in Environment and Planning B: Planning and Design (Batty 2013), "resilience seems to have become a new focus for the short-term and long-term futures of city systems." Taking the overall city as a combination of ecological, physical, and social systems, the resilient city movement is attracting attention of researchers around the world. But, in spite of its importance to the urban area, network vulnerabilities and resilience have not received sufficient research attention. The National Research Council of the USA has called for approaches to mitigate vulnerability in transportation by modelling complex adaptive systems (Godschalh 2013).

2.3 Research in sectors other than urban traffic network

The subjects of vulnerabilities and resilience have received research attention in ecological systems. Also, the freight transportation component of supply chains continues to be an area of research (Morlok and Chang 2004, Shefi 2005, Ta and Goodchild 2010, Anderson W.P. et al 2011, Miller-Hooks et al. 2012). The soft systems (e.g. ITS architecture) have been of research interest as well (Omer et al 2014).

2.4 Resilience of national or wide-area regional level highway networks

Some government agencies have taken these as subjects of research interest. For example, travel adaptive capacity analysis research has been reported by researchers in Australia and New Zealand (see Hughes 2014 for New Zealand).The objective of the research is to ensure that transport infrastructure assets and services function continuously and safely.

2.5 Metrics and models of resilience

Limited available sources report research in metrics and models of resilience (Cox 2011). The implications of the resilience objective in transportation planning have received some research attention. Metrics of resilience for the analysis and evaluation of the capacity of a network as a response to unusual conditions in the traffic environment were reported by Murray-Tuite and Mahmassani (2004), Murray-Tuite (2006), and Nelson (2013). Attempts were made to define, quantify, and combine multiple metrics of resilience into a combined index. Metrics include adaptability to unusual traffic surges and ability to recover quickly. An application of selected metrics to a test network in association with traffic assignment methods found that the "user equilibrium method" results in better adaptability while "system optimum assignment" gives better mobility and faster recovery. Operational metrics have been studied to determine a passenger transportation system's resilience to terrorism or natural disaster. As a step in the direction of modelling resilience, Murray-Tuite and Mahmassani (2004) developed a methodology for determining vulnerable links in a transportation network. Studies by Nelson (2013) are pointing in the new direction of system adaptive capacity.

2.6 Applications of Intelligent Transportation Systems (ITS)

Research has been reported on application of ITS in transportation planning to enhance adaptive capacity in order to handle recurring imbalance of demand vs. capacity as well as non-recurring incidents or operational inefficiencies or wide variation in conditions. The application of predictive methods has been suggested to make such an approach to become operational in the real world (US DOT 2002).

2.7 Active transportation and demand management

Recent studies appear to be moving in this direction to improve capacity. Federal Highway Administration (FHWA) has sponsored research intended to provide content for the active transportation and demand management (ATDM) part of the 2010 Highway Capacity Manual. These capacity-enhancing approaches are intended to prevent or delay traffic breakdown or even gridlock. The ATDM calls for continuous monitoring of the transportation system and on the basis of archived data and/or predictive methods, traffic is managed in real time. The intent is to model response to the varied demand and capacity conditions.

3. GOING BEYOND ADAPTIVE TRAFFIC CONTROL OF INTERSECTION: CONNECTED VEHICLE TECHNOLOGY AND ASSOCIATED METHODS

There is a need to go beyond the adaptive traffic control of intersections by enhancing inherent plus dynamic resilience of the traffic system at a broader spatial scale of a corridor or a wide-area road network. Connected vehicle technology and associated methods that yield resiliency measures (i.e. adaptive capacity attributes) are under study at Carleton University. Some ideas are advanced here on how to apply these resiliency measures in practice in order to address efficiency and other issues in urban transportation.

3.1 Connected Vehicles and Products

Connected vehicle technology is an outgrowth of ITS, and in turn, it relates to the technology of automation in driving (with autonomous vehicles). A second paper to be presented at this conference covers resilience enhancement with automation in driving. The connected vehicle technology is designed to enable the vehicle to share information with other vehicles and/or with the transportation infrastructure. By using computer-communications (i.e. information technology) vehicles share location and traffic environment information with nearby vehicles and if required, with infrastructure. Such capability could aid autonomous vehicles and therefore automation in driving. Although most designers believe that connected vehicles technology will be central to automation in driving, a limited perspective of advanced technology vehicles may suggest that sensor-based systems will be sufficient for an autonomous vehicle to function in traffic networks (Anderson, J.M. et al 2014).

According to recent European Commission news and an associated Report (2016), the connected vehicle in its current state of development is in essence a platform that enables the exchange of information between the vehicle and its surroundings, either through local wireless networks or via the internet. The interactions made possible by this connectivity are presented in Table 1.

Table 1: Connected vehicle features

Features	Functions
Vehicle-to-vehicle interactions (V2V)	Vehicle interacting with other vehicles
Vehicle-to-infrastructure interaction (V2I)	Vehicle interacting with infrastructure –roadside equipment Vehicle interacting with traffic management centre
Infrastructure-to-vehicle interaction (I2V)	Infrastructure (roadside and/or traffic management) interacting with the vehicle
Vehicle-to-device interaction (V2X)	Wireless communications to any device

Source: Adapted from EU Commission (2015, 2016)

The above functions imply that networked vehicles are designed to interact with their environment, which means communication, data transmission, and shared computational efforts between vehicles and infrastructure, and between vehicles and any other device. (EU Commission 2015, 2016).

Table 2 presents products that will be made possible by application of connected vehicle technology. These include mobility, safety, autonomous driving, vehicle management, entertainment, well-being, and home integration (EU Commission 2015, 2016). These products are no doubt of use to car owners, businesses, governments, and society at large. A subset of these products closely relates to enhancement of resilience in urban transportation. Specifically, mobility, safety, autonomous driving are of research interest in the resilience subject.

Technological assessment of connected vehicles suggests that this technology has the potential to make driving safer and reduce traffic congestion. These effects will be made possible by vehicle's capability to recognize and anticipate risk and dynamically calculate optimal routes. Additionally, connected cars can contribute significantly to road safety by incorporating safety features, such as the emergency call system that automatically alerts the nearest emergency centre in case of an accident (EU Commission 2015, 2016).

Connected cars can also improve energy efficiency by incorporating weather predictions, information on traffic congestion, and specific infrastructure locations in routing and driving behaviour (EU Commission 2015, 2016). In urban driving, the connected vehicle technologies can reduce idling, number of stops, and unnecessary accelerations and decelerations. Also, traffic flow at signalized intersections can be improved. Wireless data communications among enabled vehicles and roadside infrastructure can be used to broadcast signal phase and timing and geometric intersection description data to vehicle. In turn, in-vehicle systems can perform calculations to provide speed advice to the driver. This information will allow the driver to adapt the vehicle's speed to pass the next signal on green or to decelerate to a stop in the most eco-friendly manner (US DOT 2012).

Table 2: Connected vehicle products

Product	Applications
Mobility Management	These applications focus on improving traffic flow, allow drivers to reach a destination quickly, safely and in a cost-efficient manner. Examples include advanced navigation systems, traffic coordination assistance and parking lot or garage information systems.
Safety	These safety applications protect the driver, the passenger, and road users. They can be divided into hard safety and soft applications. Hard safety applications aim to avoid imminent crashes and/or minimize damage when they cannot be avoided. Soft safety applications respond to safety concerns that do not require immediate reactions. Examples of hard safety applications include blind spot warning systems and forward collision warning systems. Examples of soft safety systems include warning systems for icy roads up ahead, traffic jams, or adverse weather conditions.
Autonomous driving	This functionality involves partially or fully automatic driving. Examples of applications include operational assistance or autopilot in heavy traffic, keep-your lane systems, automated parking systems and advanced adaptive control systems.
Vehicle management	These applications aid the driver in reducing operating costs and improving ease of use (e.g. dynamic vehicle service).
Entertainment	Entertainment of passengers and the driver is the focus here. Examples include embedded WLAN hot spots, music video streaming. Also, social media integration and a smart phone interface is a part of this product.
Well-being	These applications impact a driver's comfort, ability and fitness to drive. Examples include fatigue detection systems and alert calls for medical assistance.
Home integration	This emerging application area integrates vehicle systems with those at home.

Source: Adapted from EU Commission (2015, 2016) and Khan et al (2012, 2014).

Connected vehicle technologies will enable traffic engineers to optimize traffic signals for a selected objective function. If the objective is eco-drive, the signals will be optimized to reduce fuel consumption and emissions using connected vehicle data (US DOT 2012). Equipped signals can be programmed using connected vehicle data to give priority to emergency vehicles, transit vehicles or freight vehicles approaching a signalized intersection that request signal priority. These applications use data on vehicle's location, speed, and vehicle type (e.g. emergency vehicle, public transit). In the case of public transit, its adherence to schedule or number of passengers can be considered in granting priority (US DOT 2012).

For achieving the resilience-enhancing objective, the signal optimization can be carried out to accommodate traffic surges. These applications collect data from vehicles, such as vehicle location, speed, and from infrastructure-based devices on traffic volume. These data will be used to determine the optimal operation of the traffic signal system.

For freeways and other highways, connected vehicle technologies can be used to develop resilience in handling traffic surges. Specifically, the following measures can be enabled: adaptive metering of ramps (if needed for integrating freeway-arterial corridors), variable speed advice, diversion to alternate routes, etc.).

4. SOME POTENTIAL APPLICATIONS

Priority research, development and demonstration (R, D & D) activities are underway in a number of countries on connected vehicle services with favourable benefit-cost estimates and market potential. A large number of service bundles were identified by the European Commission (2016). These are a part of EU objectives to accelerate in order to catch up on RD&D and commercial products for connected vehicles. The European Commission report on the platform for the Deployment of Cooperative Intelligent Transport Systems in the European Union (C-ITS Platform) released in January 2016 provides details. These are under study in order to establish research programs in technical, socio-economic, and policy areas.

A number of potential applications referenced above will enhance resilience of the transportation system. Table 3 presents selected applications in terms of their description and enabling technologies. Table 4 uses this information in defining resilience measures enhanced by connected vehicle services and associated methodologies.

5. EXAMPLE OF POTENTIAL APPLICATION

A key resilience attribute is to have knowledge of prevailing traffic conditions en-route as well as on alternate routes that are available for smart routing of traffic overloads in a dynamic manner in the event of a major event. If the traffic overload is not handled, a traffic disruption will occur. With the availability of projected connected vehicle services, it is feasible to develop next generation traveller information systems. These information systems can potentially offer enhanced benefits, provided that methodological innovations can be integrated with the rapidly developing technology of connected vehicles. The technologies of data capture and delivery are projected to evolve in the short-to-medium term. The data can be processed and fused for developing special purpose models for use in next generation traveller information and route guidance systems. This section reports an example application of connected vehicle services in association with the Bayesian approach to integration of technology and methods in predictive travel time modelling and smart route guidance. Details of the Bayesian method are presented in Khan (2013).

Table 3: Selected connected vehicle services with potential to enhance network resilience

Services	Technologies	Application
Traffic jam ahead warning	V2V	Urban and highway
Slow or stationary vehicle(s)	V2V	Urban and highway
Traffic information & smart routing	V2I	Urban and highway
Emergency electronic brake light	V2V	Urban and highway
Emergency vehicle approaching	V2V	Urban and highway
Hazardous location notification	V2I	Highway
Road works warning	V2I	Highway
Weather condition	V2I	Highway
Shockwave damping	V2I	Highway
Probe vehicle data	V2I	Highway
In-vehicle speed limit	V2I	Highway
In-vehicle signage	V2I	Highway
Time to green at signal ahead	V2I	Urban
Traffic signal priority request by designated Vehicles	V2I	Urban

Source: Extracted from European Commission (2015, 2016).

Route and network component-specific traffic environment is unpredictable under conditions of traffic incidents or other potentially disruptive events. Commuters who are very familiar with their usual travel route cannot be sure about prevailing traffic flow conditions that reflect a multitude of influences. Some of these are incidents, road works, and road weather conditions. It is logical that there is a growing market for information on traffic conditions (i.e., travel time and delay) prior to and during travel to work or other destinations.

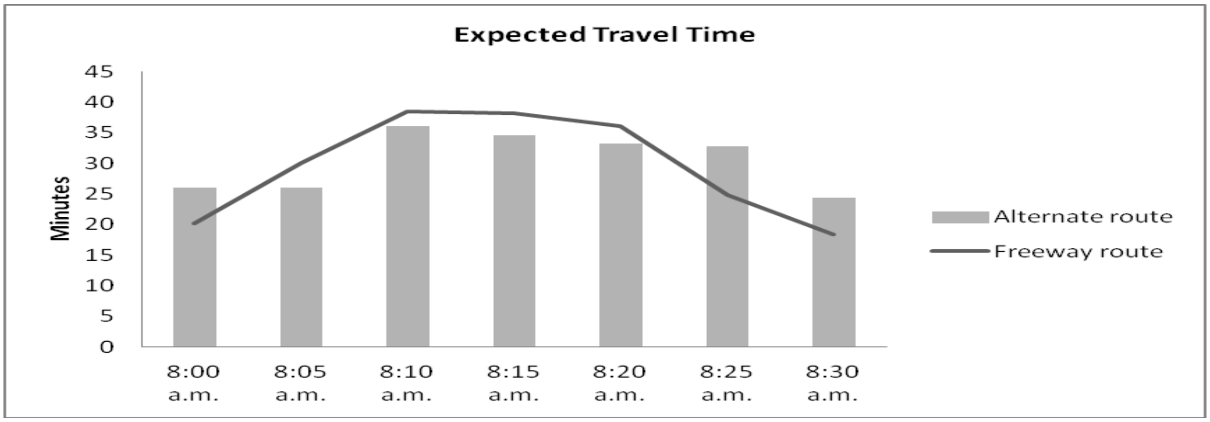
Research at Carleton University has resulted in the concept design of the predictive travel speed and travel time system that encompasses modules for the acquisition of real-time information, prediction of travel time by the route/network performance model, fusion of real time information from connected vehicles or other sources, with model-produced information, and dissemination of result to road users (Figure 1). This concept design is based on the technical aspects of new generation ATIS that will be made possible by the availability of connected vehicle data. The theoretical basis as well as the operational aspects of the predictive travel time methodology is described by Khan (2010). The relationships between variables and the sequence of steps for computing expected travel speed and time are presented in Figure 1.

Table 4: Resilience measures enhanced by connected vehicle services and associated methodologies

Resilience Measure	Connected vehicle services and other actions	Connected vehicle technologies and associated methods
Inherent resilience		
Traffic and geometric design of roads and highways with built-in flexibility to accommodate random traffic overloads	Simulation studies to test designs	Microsimulation of traffic
Intelligent roadside and traffic control centre with capability for two-way communications with vehicles	Design of intelligent infrastructure (roadside and control centre)	Simulation studies of data transfer and analysis
Dynamic resilience		
Dynamic inventory of traffic loads in various parts of the network and assessment of available capacity to handle diverted traffic	Traffic jam ahead warning, slow or stationary vehicle(s), electronic brake light, emergency vehicle approaching	V2V
	Hazardous location notification, road works warning, weather condition, shock wave damping, probe vehicle data, in-vehicle speed limit, in-vehicle signage, time to green.	V2I
Smart routing options based on system optimal or dynamic traffic assignment and traffic diversions	Traffic information & smart routing	V2I, system optimal or dynamic traffic assignment, Montecarlo and Bayesian methods.
Post-event transition to normal and establishing strategies for future events	Simulation of transition.	V2I data used for planning future active safety strategies.

This example application is on diverting traffic overload to an alternate route. The availability of an alternate route and the ability to divert traffic overloads is an attribute of resilience. The location of the application is Ottawa (Canada) (Figure 2). The freeway route, and the alternate route (based on Fallowfield Road and other arterials) are shown. In travel environments characterized by high traffic surges or incidents, the freeway route may no longer be the quickest route. Therefore drivers should be given this information in order to avoid overloading the already congested freeway route. This will encourage diversion of some traffic to the alternate route. Travel speed data can be contributed by connected vehicles on a real time basis which in turn can be used to compute travel time to a location of interest downstream.

Repeated applications of the predictive space mean speed and travel time methodology presented in Figure 1 resulted in expected travel time information via two routes (Figure 2). On the basis of results, dynamic route guidance information can be developed as shown in Table 5.



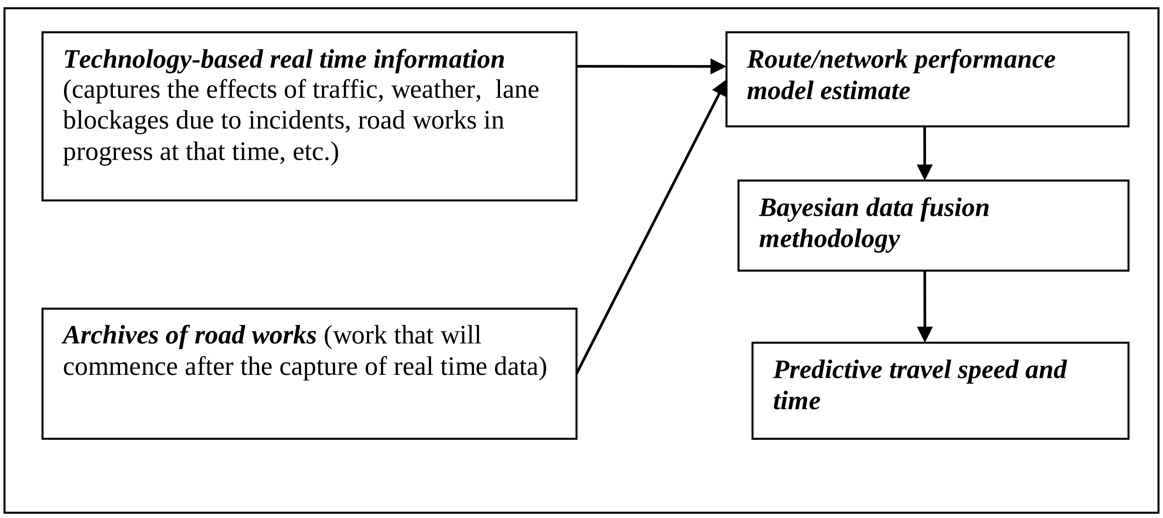


Figure 1: Methodological framework (Source: Khan 2010)

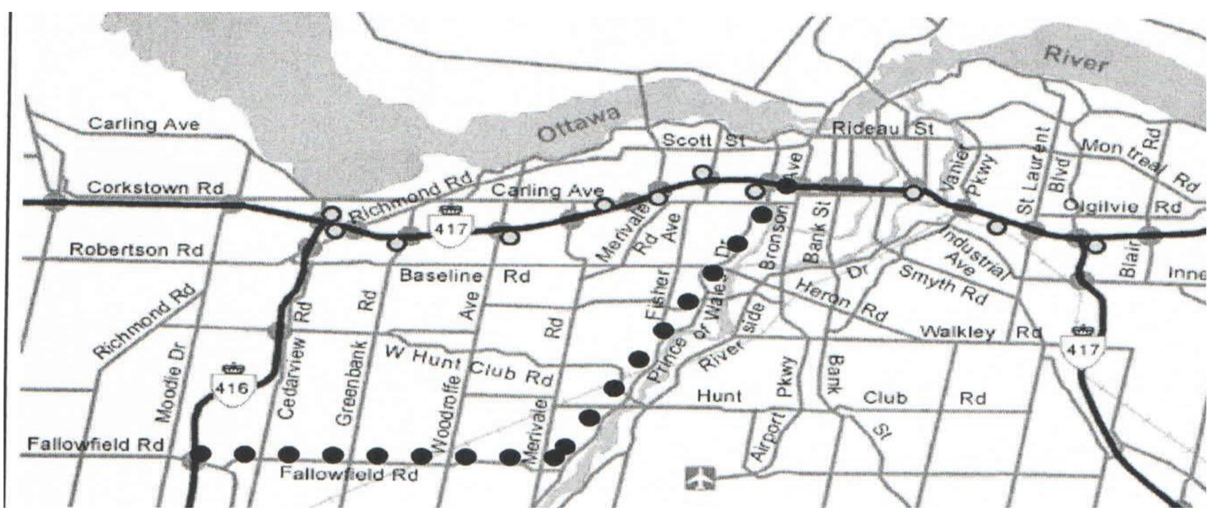


Figure 2: Example route alternatives (Ottawa, Canada)
(Source of map: courtesy Ministry of Transportation, Ontario, website) Source: Khan 2010

Table 5: Route guidance information

Time period starting	Expected travel time via Freeway route (min)	Expected travel time via Alternate route (min)	Comment
8:00 a.m.	20.2 (best)	26.00	There is no need to show alternate route information
8:05 a.m.	30.0	26.00 (best)	Alternate route advice can be given to divert some traffic from the freeway route
8:10 a.m.	38.5	36.00 (best)	Alternate route advice can be given
8:15 a.m.	38.23	34.50 (best)	Alternate route advice can be given
8:20 a.m.	36.13	33.23 (best)	Alternate route advice can be given
8:25 a.m.	24.86 (best)	32.74	There is no need to show alternate route information
8:30 a.m.	18.34 (best)	24.40	There is no need to show alternate route information

Adapted from Khan 2010.

6. CONCLUSIONS

1. Resilience of traffic networks is an emerging field of research that is aimed at overcoming vulnerabilities, preventing disruptions if possible, and reducing the severity of impacts.

2. In addition to improving the inherent resilience by improving traffic design of the network (including geometrics), there is much that can be done to enhance active/proactive traffic management in the form of dynamic resilience.

3. Connected vehicles technology has the potential to enhance resilience of traffic networks.

4. Connected vehicles is a medium-term initiative and plans for services are under development. Selected services that are aimed at mobility and safety can be used for enhancing resilience of traffic networks.

5. Automation in driving is a long term initiative and there are no firm answers on how autonomous vehicles in large numbers will become a part of the traffic flow without changes to the infrastructure. Also, contrary to some views expressed in the literature, automation in driving will require connected vehicle features. Therefore, it is likely that automation in driving will enable resilience enhancement in traffic networks. The reader is advised to see a second paper presented at this conference.

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