RESILIENT INFRASTRUCTURE
June 1–4, 2016

AUTOMATION IN DRIVING FOR ENHANCING RESILIENCY IN TRANSPORTATION SYSTEM

Ata M. Khan
Carleton University, Canada

Matthew Whelen
Carleton University, Canada

Omar Elsafdi
Carleton University, Canada

Naser Snobar
Carleton University and Morrison Hershfield, Canada

Brooke Jones
Carleton University, Canada

Patricia Arnold
Carleton University, Canada

ABSTRACT

The ability of the transportation system to continue to serve traffic under disruptive conditions is a resilience characteristic of infrastructure and traffic management. In the context of this research, resilience is defined as the ability to resist the loss of traffic-serving capability by using traffic (including geometric) and control system design advances (i.e. the inherent resilience) and by activating capacity-enhancing measures (i.e. the dynamic resilience). Vulnerabilities in road traffic networks cause the loss of capability to serve demand overloads. On the other hand, intelligent technology and associated methodology can potentially prevent or reduce this loss of capability. An outstanding research question is the role of automation in driving for enhancing the resilience of urban road traffic network. This paper reports research in-progress on improving resilience of adaptive capacity in traffic networks with intelligent systems and advanced methods. An introduction is provided to vulnerabilities in traffic network, and available information is used as empirical evidence of vulnerabilities. Inherent and dynamic resilience measures of the traffic system are defined at the scales of corridors and networks that can potentially overcome vulnerabilities. Features of autonomous driving are presented as resilience-enhancing measures. Finally, conclusions are presented on the potential of automation in driving to enhance the resilience of urban traffic network so that it can withstand high predictive imbalances of demand vs. capacity as well as stochastic traffic overloads and recover functionality at a tolerable level of performance within an acceptable time period.

Keywords: Resilience, traffic, intelligent transportation system, autonomous driving, networks, adaptive capacity

1. RESEARCH CHALLENGES

The subject of physical resilience of infrastructure is receiving due research attention around the world. There is another facet of the resilience subject that also requires research attention. It is resilience in traffic handling capability that is needed to overcome vulnerabilities in the network. Without resilience measures, traffic disruptions are highly likely. This paper reports research in-progress on vulnerabilities in road traffic network in terms of risk of severe loss of capability to serve demand, and intelligent technology-assisted methods for improving the resilience of adaptive capacity.

From a long term perspective, the research program underway is aimed at enhancing the adaptive capability of urban transportation by using resiliency measures in traffic system development and operation. To achieve this long term objective, it is intended to contribute new knowledge on how advanced methods in association with intelligent systems (e.g. connected-vehicles, other technologies of automation in driving) can further improve resiliency attribute for enhancing adaptive capacity of urban road traffic networks so that efficiency and other issues of transportation can be addressed in a more effective manner than can be done today with existing knowledge.

2. VULNERABILITIES IN TRAFFIC NETWORK

The road traffic network serving an urbanized region is subjected to recurring major traffic overloads in traffic demand and there is a general lack of adaptiveness in the system to handle such traffic surges. The cause of this phenomenon relates to planning urban and regional transportation systems under uncertainty. Planners use long-term forecasts of land use and the knowledge of the interaction of land use and transportation systems in devising the most suitable multimodal infrastructure and operations plan to meet the person and goods movement requirements for future years. There are uncertainties in population and economic activity forecasts and a well-known issue is the joint land use and transportation system plan may not be implementable exactly as modelled by the planners. Therefore, it is likely that over time there will be imbalances in travel demand and available capacity in some parts of major travel corridors and the central city transportation network.

In shaping the configuration and geometry (i.e. the traffic design) of the road network, designers use future year origin-destination modal travel demand patterns that are subject to uncertainty. Although, attempts are made over time to accommodate predictive recurring mismatches of peak period travel demand and available capacity in some high traffic components of the overall regional network through traffic and demand management measures, there is very rarely a satisfactory accommodation of peak period traffic surges.

To make matters worse, there is a lack of built-in flexibility in the network to handle traffic overloads caused by stochastic events that cannot be known ahead of time. These random surges of traffic could be caused by incidents (e.g. major traffic cpllisions), severe weather-related disruptions (some induced by long-term climate change), and many other nature-induced or man-made disruptions. Evidence-based information indicates that such disruptions are responsible for a very high percentage of delays and other adverse effects. Although advances in traffic control and traffic management made possible by intelligent transportation systems play a role in lessening the adverse effects, there is a need for additional measures to manage the effects of such disruptions. Table 1 presents vulnerabilities, root causes and potential solutions. The following sections provide additional information on potential solutions.

Table 1 Vulnerabilities, root causes and potential solutions

Vulnerability	Root causes	Potential solutions
Lack of flexibility - inability to adapt to traffic overloads; inability to predict on a short-time basis the onset of severe traffic disruption; inability to shift traffic quickly to alternate routes that have the capacity to handle diverted traffic.	Planning under uncertainty of traffic demand & localized traffic design deficiencies; predictive imbalance of demand vs. capacity; random events – traffic incidents; severe weather, etc.	Inherent resilience provided by new design approaches and intelligent infrastructure; dynamic network level resilience enabled by knowledge of traffic condition in the network obtained from data contributed by connected-vehicles/other technologies of automation in driving, and application of data in smart route guidance system.

3. INHERENT AND DYNAMIC RESILIENCE

The subject of inherent (also called static) and dynamic resilience of adaptive capacity in urban traffic networks can be considered as “new and developing”. Although the benefits of adaptive traffic control became clear 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 recurring major changes in traffic demand as well as stochastic non-recurring surges of traffic. As noted earlier, these random surges of traffic could be caused by incidents (e.g. traffic accidents), severe weather-related disruptions (some induced by long-term climate change), and many other nature-induced or man-made disruptions.

Resilience is defined as the ability to resist the loss of traffic-serving capability by using traffic (e.g. geometric) and control system design (i.e. the inherent resilience) and by dynamically activating capacity-enhancing measures (i.e. the dynamic resilience). Adaptive traffic control of signalized intersections was an initial step in this direction more than a decade ago. Available information suggest that its installations have progressed well (Jagannathan and Khan 2001, Stevanovic 2010). But, there is a need to go beyond this technology by enhancing inherent plus dynamic resilience of the traffic system, especially at a broader spatial scale of a corridor or a wide-area road network so as to withstand severe traffic overloads and recover functionality at a tolerable level of performance within an acceptable time period. Available information suggests that such predictive but very high imbalances of demand vs. capacity, as well as stochastic severe traffic shocks, occur frequently. Considering that some links in the traffic network serve private as well public travel modes, opportunities as well as challenges increase.

Research products that integrate intelligent technology, predictive models, and decision aids for traffic management are needed for enhancing “resilience of adaptive capacity” for overcoming 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 routes selected by motorists as well as in diversion routes that may be used to prevent severe congestion.

Although there are many facets of resilience of the urban transportation system, research underway focuses on improving the resilience of adaptive capacity in traffic networks with intelligent systems and advanced methods. If 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, their usefulness will rise considerably.

Available research products are serving as building blocks for current research. These and additional products will be integrated 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).

4. ROLE OF AUTOMATION IN DRIVING TO ENHANCE RESILIENCE

To determine if automation in driving has the potential to enhance the resilience of traffic networks, we review developments in automation and relate technological and methodological capabilities to resilience attributes. Due to advances in information and communication technology (ICT), the profession has advanced much beyond the intelligent vehicle and highway system (IVHS) initiative of many decades ago and now is the era of developing and testing connected and autonomous vehicles.

Further research is needed for improving automated systems and guiding the application of promising technologies for the benefit of road users, the economy and society at large. The resilience of traffic networks is one such worthy endeavour. In support of the research community, public agencies can create programs for guiding new systems in the direction of delivering benefits that are within reach. Such programs can be of immediate use to public agencies in regards to knowing how their mandate to plan and operate road network is likely to change, should these new systems (i.e. automation in driving technologies) be accepted in the mass market.

4.1 Level of technological advances

Khan, Bacchus and Erwin (2012) provide a projection of technological advances and approximate time frame as a part of the paper on policy challenges of increasing automation in driving. See Figure 1. These have progressed along the continuum between conventional fully human-driven vehicles and autonomous vehicles, which partially or fully drive themselves and which may ultimately require no driver at all.

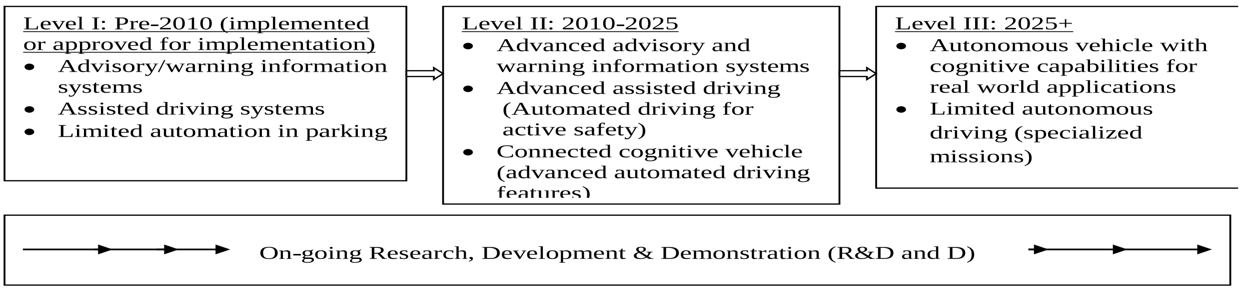

Fig.1. Levels of technological advances and approximate time frame

Along this continuum are notable automated vehicle technologies that enable a vehicle to assist and make decisions for a human driver. The automated driving functionality can be built upon 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. A subset of developing technologies are packaged as driving assistance systems and include crash warning systems, adaptive cruise control, lane-keeping systems, and self-parking technology. The US National Highway Traffic Safety Administration (NHTSA) has created a five-part taxonomy to help clarify this continuum (described by Anderson et al 2014). These are summarized in Table 2.

Table 2: Level of automation in driving

Level of automation	Description
Level 0	No-Automation: The human driver is in complete of all functions of the vehicle
Level 1	Function-specific Automation: One or more specific control functions are automated and these operate independently of each other. But, the driver has overall control.
Level 2	Combined Function Automation: This level involves automation of at least two primary control functions designed to work in unison to relieve the driver of control of those functions (e.g. steering and acceleration); shared authority when the driver cedes active primary control in certain limited driving situations; the driver must remain attentive all the time.
Level 3	Limited Self-Driving Automation: The vehicle enables the driver to cede full control of all safety-critical functions under certain traffic or environmental conditions; transition back to driver control under defined conditions. The driver is expected to be available for occasional control.
Level 4	Full Self-Driving Automation: The vehicle is designed to perform all safety-critical driving functions and monitor roadway conditions for an entire trip; the driver provides destination or navigation input; applies to both occupied and unoccupied vehicles. By design, safe operation rests solely on the automated vehicle system.

Adapted from Anderson et al. (2014)

There are different views on how autonomous vehicle technology and connected-vehicles technologies relate to each other. Some technology developers believe that these are closely related, and others consider that autonomous vehicles can function on sensor data alone and need not consider obtaining data from other vehicles (Anderson et al 2014). Connected vehicles are designed to share information with other vehicles or the transportation infrastructure (EU Commission 2016).

If vehicles share location information with each other within a certain distance via information technology, this could aid autonomous vehicles. Taken a step further, if vehicles share sensor information with nearby vehicles, this could give an autonomous vehicle additional information that could be used in decision-making. In order to take advantage of these technological capabilities, it a common belief among researchers that connected vehicle technology will be central to achieving automation in driving (Anderson 2014, EU Commission 2015, 2016).

The role of the human driver and the driver-vehicle interface continue to be of research importance. At hand, there is lack of consensus on the full autonomy for the vehicle, according to researchers and automotive industry experts, the next step is the development of a cognitive vehicle which will integrate intelligent technology and human factors for providing non-distractive interface for safety, efficiency and environmental sustainability in driving. A cognitive connected vehicle can function in highly automated and fully autonomous mode (Khan et al. 2014).

Table 3 describes the capabilities of a cognitive connected vehicle. Technological forecasts suggest that a number of cognitive vehicle features can be achieved with R&D efforts (Heide et al 2006, Hoch 2007).

Table 3: Cognitive vehicle features for human and machine control

Cognitive vehicle features	Features for human control	Features for adaptive longitudinal and lateral control system
Awareness of position and surroundings	X	X
Ability to gather data and transmit data	X	X
Ability to process data	X	X
Ability to cooperate/collaborate	X	X
Communication for active safety		X
Informs the driver about situations (warnings, advice)	X	
Diagnostic capability	X	X
In case of crash, capability to send and receive information	X	X
Ability to provide non-distractive user interface	X	X
Infotainment capability	+	+

+ This feature does not relate to traffic service and safety objectives. Source: Khan et al 2014

The above brief review indicates that over the years, the vision of the *intelligent vehicle* became increasingly ambitious. An intelligent vehicle in its advanced form should have cognitive features that mimic non-distracted and non-aggressive driving tasks. A *cognitive vehicle* is intended to assist the driver, and if necessary in dangerous conditions, it has the capability to take corrective active safety action if the driver is incapacitated or highly distracted or if the driver wishes the vehicle to take over driving for a limited duration of time. However, driving an intelligent cognitive vehicle does not take the driver out of the loop. The design attributes of a cognitive vehicle are influenced by human factors in driving. According to a recent news article, development of 'human-like' self-driving technologies is attracting investor capital (Traffic Technology Today 2016).

Research is underway at Carleton University in a number of facets of the cognitive vehicle and automation in driving (Figure 2). Subjects covered include resilience, traffic infrastructure and operations for automation in driving, human factors, eco-driving, safety surrogate measures, and algorithm development for active safety and very high level of automation in driving.

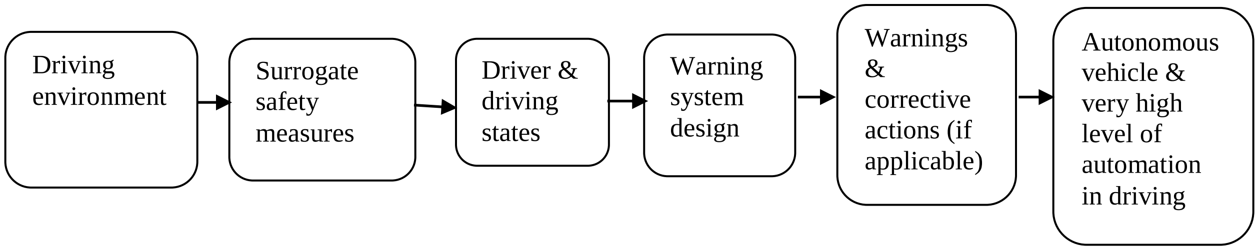

Figure 2: Cognitive connected vehicle research framework

4.2 Contribution of Automation in Driving to Resilience

Connected cognitive vehicles can be developed with capabilities to enhance resilience of the traffic network. Table 4 provides a summary of resilience measures that benefit from developments in various attributes of connected vehicle technologies that enable automation in driving.

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

Resilience Measure	Connected vehicle services and other actions	Connected vehicle technologies and associated methods
<u>Inherent resilience</u>		
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
<u>Dynamic resilience</u>		
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	Vehicle-to-vehicle (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.	Vehicle-to-infrastructure (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

From a resilience perspective, automation in driving offers the possibility of fundamentally changing transportation. Vehicles equipped with automation technologies have much potential in reducing crashes and improving mobility (Anderson et al 2014). Section 4.4 of this paper provides an illustration of the need and potential role of automation in enhancing mobility and safety, which in turn will enhance resilience.

Autonomous vehicle technology will offer opportunities to avoid routes and links affected by incidents and other events and therefore, contribute to the resilience characteristics of the network. It can also enable the achievement of eco-drive objective. Smoother acceleration and deceleration that can be achieved with automation can enhance fuel economy by 4-10%. Shortening headways without compromising safety can be achieved by automation technologies. A platoon of closely spaced autonomous vehicles that stops or slows down less often resembles a train. This pattern of traffic flow improves travel time (European Commission 2015 and 16, Anderson et al. 2014).

Autonomous vehicles, if introduced in traffic networks with due attention to planning principles and by adding intelligent devices to the infrastructure intended for vehicle-to-infrastructure interaction, can improve capacity and reduce traffic congestion. The carefully planned introduction of automated vehicles in the traffic network could enable greater vehicle throughput on existing roads than obtainable now. The interactions between vehicles and between vehicles and infrastructure will enable constant monitoring of surrounding traffic and responding with finely tuned braking and acceleration adjustments. These capabilities should enable automated vehicles to travel safely at higher speeds and with reduced distance headway between vehicles. Research indicates that the platooning of connected vehicles could increase lane capacity (i.e. vehicles per lane per hour) significantly (Anderson et al 2014 – based on their literature review).

In more congested travel conditions, automated vehicles could help to avoid the inefficient stop-and-go traffic operation — a result of the exaggerated braking and acceleration responses of inattentive human drivers. This driving pattern leads to a severe degradation in vehicle throughput of the traffic network. In uninterrupted traffic flow on highways, the volume of traffic served (i.e. throughput) forms a backward bending curve, as illustrated below in Figure 3. Autonomous vehicles, can reduce start-and-stop traffic through more finely controlled braking and acceleration, should enable higher throughput during peak travel hours.

Further information on the two broad categories of traffic congestion is in order. These are recurrent delays and non-recurrent delays. Recurrent delays occur due to congestion during same time period and at the same location on a daily basis. These are the result of demand vs. capacity imbalance (i.e. prevailing travel patterns in which the number of vehicles trying to use a road with inadequate traffic and geometric design at the same time exceeds the capacity of the road). Non-recurrent random delays, in contrast, occur due to isolated events, severe weather, a large sporting event, a disabled vehicle, or a traffic crash. These normally reduce capacity or create a demand overload. If highway works are not planned carefully, and road users are not informed ahead of time, a similar effect can be expected. Evidence-based information suggests that non-recurrent congestion accounts for roughly a half of all congestion delays (Anderson et al. 2014).

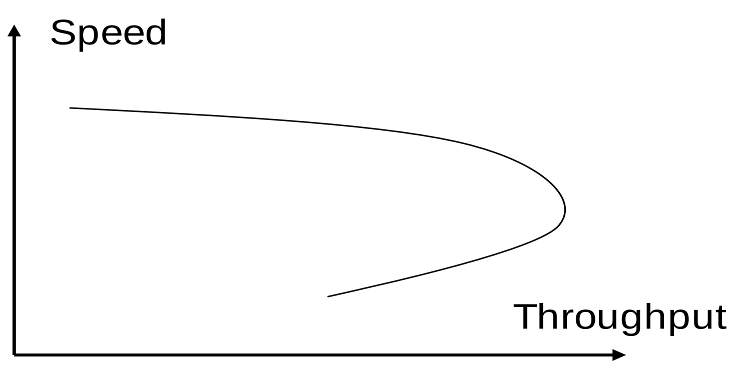

Figure 3: Highway traffic throughput as a function of operating speed (Illustration of effect of traffic overload). Source: Anderson et al (2014)

A key rationale for developing automated vehicles is to reduce accidents. If such vehicles are bought by consumers and the level of automation reaches to Level 4 noted in Table 2, traffic incidents are likely to reduce dramatically. A pre-requisite is that the traffic control system is able to accommodate automation in driving in every aspect for safe and efficient operation even when automated vehicles will co-exist with non-equipped vehicles. This is an area of further research at Carleton University.

4.3 Illustration of a Role for Automation in Driving for Enhancing Resilience

Frequently, a driver within the traffic stream finds it necessary to decelerate at a very high rate in order to avoid a collision with the lead vehicle which applied brakes to reduce speed for some unknown reason. Another situation that necessitates hard braking is when a vehicle abruptly changes lanes and joins the traffic stream in front of the driver. In these and many other similar situations, drivers that are not assisted with automation features send shock waves in the traffic stream that sometimes result in traffic accidents. In such traffic environment, even the most favourable outcome is delays experienced by a large number of motorists.

In order to illustrate driving without automation features, data from a driving simulator was used. A snapshot of driving trajectories was extracted from a simulation run that ranged from time stamp 778 sec to 792 sec, and it included the incident of "Lead Car Brake" at time stamp 779.2 seconds. Results shown in Figures 4 to 7 appear to be very logical for the driving environment.

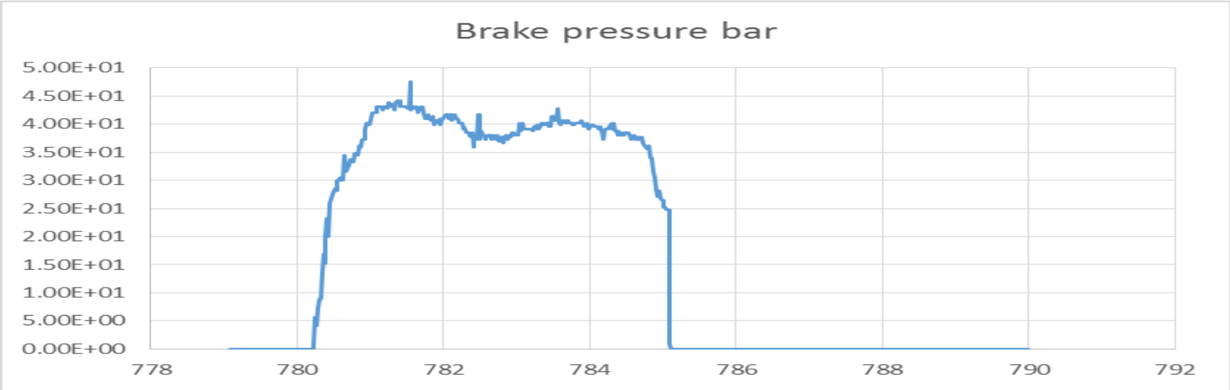

Figure 4: Brake action under human control

Notes: (1) Horizontal axis is time stamp (sec). (2) Vertical axis is brake pressure. (3) Lead car brakes at time stamp 779.2 (sec).

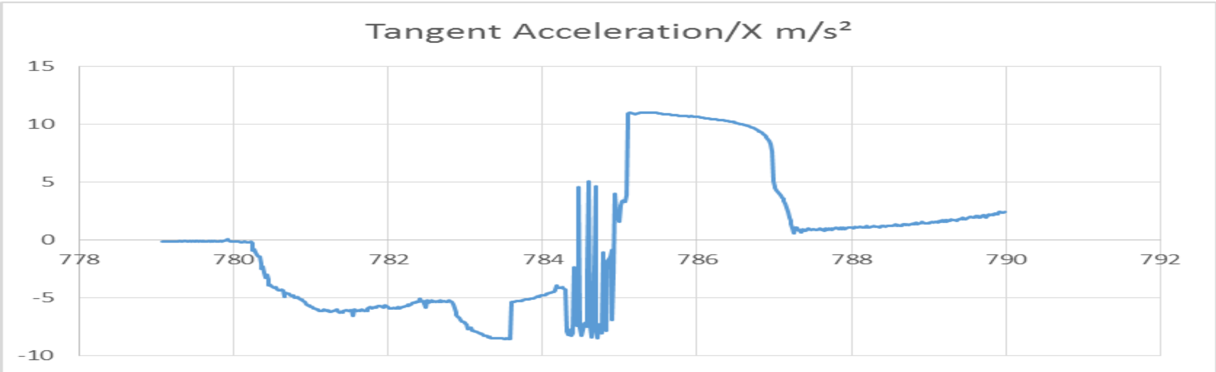

Figure 5: Tangential acceleration under human control

Notes: (1) Horizontal axis is time stamp (sec). (2) Vertical axis is acceleration/deceleration (m/sec/sec). (3) Lead car brakes at time stamp 779.2 (sec).

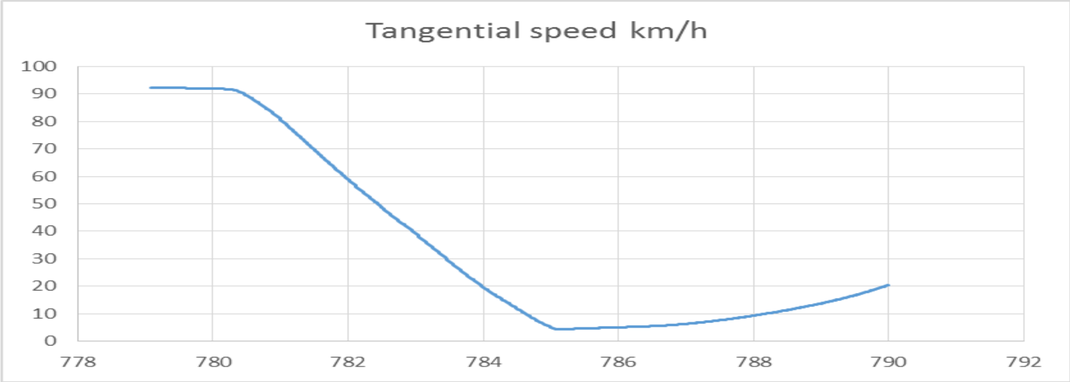

Figure 6: Tangential speed (km/h) under human control
Notes: (1) Horizontal axis is time stamp (sec). (2) Vertical axis is tangential speed (km/h).
(3) Lead car brakes at time stamp 779.2 (sec).

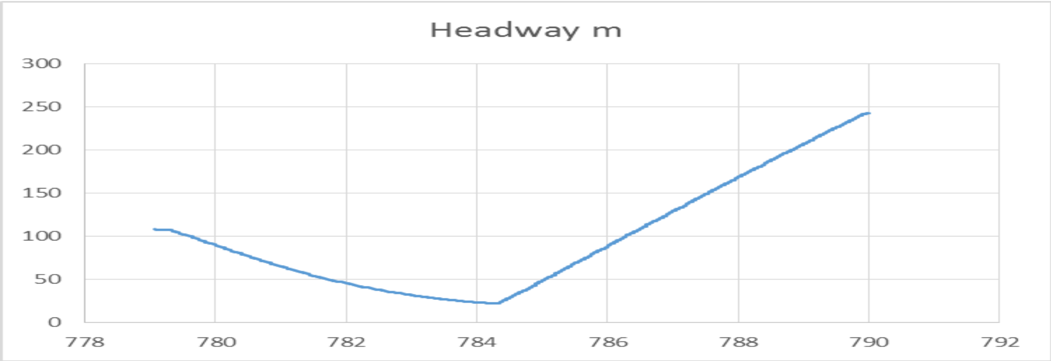

Figure 7: Distance headway (m) under human control
Notes: (1) Horizontal axis is time stamp (sec). (2) Vertical axis is distance headway (m).
(3) Lead car brakes at time stamp 779.2 (sec).

If vehicles are equipped with driving assistance or if vehicles are operating in the automated mode, the following driver actions can be avoided: (1) Distracted and/or aggressive driving. (2) Abrupt and risky actions such as a lane change manoeuver without sufficient gap in traffic. (3) Become distracted first and then to avoid a collision decelerate at a very high rate, (4) In extreme conditions, rear or a sideswipe collision.

So, automation in driving can play an important role in maintaining a safe, efficient and productive driving environment for individual automated vehicles as well as platoons. The result can be higher throughput due to safer and closer headways and higher speeds. These driving conditions enhance resilience in the network.

In the event of a nature-induced or any other disruption to traffic flow in major travel corridors or networks, the connected vehicles capability of automation in driving can identify alternate routes with available capacity to accommodate traffic overloads, and smart route diversion will come into effect as a dynamic resilience measure. The end result will be reduced adverse effect of disruption, and orderly and expedient recovery.

5. CONCLUSIONS

(1) Networks serving urbanized regions are vulnerable to severe traffic overloads, caused by imbalance of demand vs. capacity or by random events such as accidents or a number of other phenomenon including severe weather. These vulnerabilities can be addressed by inherent and dynamic resilience.
(2) The inherent resilience can be developed by using advances in the design of traffic infrastructure, including equipping the infrastructure with intelligent technologies that will serve the needs of automation in driving.
(3) Connected cognitive vehicle technology in highly automated or fully automated modes offers the potential to enhance the dynamic resilience of the traffic network.

(4) Contrary to some views expressed in the literature, automation in driving will require connected vehicle capability.
(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 traffic management infrastructure. In order to obtain answers, further research is required in measures for efficient and effective integration of connected cognitive vehicles in traffic operations.
(6) Information presented in this paper suggests that automation in driving has potential to enhance the resilience of urban traffic network so that it can withstand recurrent high imbalances of demand vs. capacity as well as stochastic traffic overloads, and recover functionality at a tolerable level of service within an acceptable time period.

6. ACKNOWLEDGEMENTS

The views expressed in this paper are those of the authors and do not necessarily reflect views of our employers or sponsors of our research. Financial assistance received from the Ministry of Transportation of Ontario and the Natural Sciences and Engineering Research Council (NSERC) of Canada is gratefully acknowledged.

7. REFERENCES

Anderson, J.M., Karla, N., Stanly, K.D., Sorensen, P., Samaras, C., Oluwatola, O.A., 2014. Autonomous vehicle technology: A Guide for Policymakers. Rand Corporation.

Armstrong, J.M. and Khan, A.M., 2008. Optimization of corridor traffic flow using dynamic Bayesian decision networks. 10th International Conference on Applications of Advanced Technologies in Transportation, Greece, Athens, 2008-05-15, Conference Proceedings CD.

European Commission, 2016. EU accelerates connected vehicles. ITS International, 25 January 2016. And C-ITS Platform, Final Report, January 2016.

European Commission, 2015. Connected cars. Business Innovations, Internet of Things, Case study 43, Feb. 2015.

Jagannathan, R. and Khan, A.M., 2001. Assessment of Traffic Adaptive Control Systems. ITE Journal, June 2001. Pp.28-33.

Gryz, T., Armstrong*, J., and Khan, A.M., 2007. Role of Simulation in Assessing Intelligent Technology for Sustainable Mobility: Example of Toll Routes and Toll Lanes. Annual Conference of the Canadian Society for Civil Engineering. June 6-9, 2007, Yellowknife, pp.315-324.

Heide, A., and Henning, K. 2006. The "cognitive car": A roadmap for research issues in the automotive sector. *Annual Reviews in Control* 30(2006), pp.197-203.

Hoch, S., Schweigert, M., Althoff, F., 2007. The BMW SURF Project: A contribution to the Research on Cognitive Vehicles", *Proceedings of the 2007 IEEE Intelligent Vehicle Symposium*, Istanbul, Turkey, June 13-15, 2007, ThB1.26, pp.692-697).

Khan, A.M., Bacchus, A., Erwin, S., 2012. Policy challenges of increasing automation in driving. IATSS Research Journal, Elsevier. 35(2), 79-89.

Khan, A., Bacchus, A. and Erwin, S., 2014. Surrogate safety measures as aid to driver assistance system design of the cognitive vehicle. IET Intelligent Transport Journal, Volume 8, Issue 4, p.415-424.

Mucsi, K., Khan, A.M., and Ahmadi, M., 2011. An adaptive neuro fuzzy inference system for estimating the number of vehicles for queue management at signalized intersections. Transportation Research Part C19 (2011) 1033-1047.

Qin, X. and Khan, A.M., 2012. Control strategies of traffic signal timing transition for emergency vehicle pre-emption. Transportation Research Part C 25 (2012) 1-17.

Stevanovic, A., 2010. Adaptive Traffic Control Systems: Domestic and Foreign State of Practice, a Synthesis of Highway Practice. NCHRP Synthesis 403, Transportation Research Board, 2010.

Traffic Technology Today 2016. News: Autonomous vehicle software developer secures funding for 'human-like' driving, February 5, 2016.