FULLY AUTONOMOUS VEHICLES: ANALYZING TRANSPORTATION NETWORK PERFORMANCE AND OPERATING SCENARIOS IN THE GREATER TORONTO AREA, CANADA

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INTRODUCTION

In recent years, major car manufacturers and technology companies have made significant advancements in the area of fully autonomous vehicles (AVs). AVs will change the transportation system and are purported to create substantial benefits for society. These include a significant reduction in deaths and injuries from traffic accidents by eliminating driver error, and the provision of independent mobility for non-drivers, including the elderly and other mobility-constrained populations. For drivers, AVs change previously unproductive travel time into productive time or time for leisure. Reduction in fuel consumption and emissions due to more foresighted driving and optimized acceleration and deceleration behavior promise significant environmental benefits on a per-kilometer-travelled basis. From a transportation performance perspective, increased roadway capacity under AV operating scenarios has the potential to substantially reduce congestion, thereby reducing travel times and emissions (Luettel, Himmelsbach, & Wuensche, 2012).

This paper analyzes transportation system performance implications of AVs by simulating operating scenarios in the Greater Toronto Area (GTA), Canada. The focus is on assessing travel time and congestion reduction benefits resulting from increased roadway capacity at different levels of AV market penetration. AVs are expected to influence congestion through two opposing forces. On the one hand, AVs do not rely on human reaction time and can safely enable small inter-vehicle spacing. AVs also drive in a more foresighted manner with precise control over acceleration which reduces the propagation of disruptive traffic waves. On the other hand, AVs will likely encourage more travel by previously less-mobile populations, reduced congestion may induce additional demand, and travel by empty vehicles may negate some congestion benefits.

LITERATURE REVIEW

Capacity Improvements and Congestion Reduction

AVs have the potential to significantly improve the capacity of roadways, with consequent benefits in the form of reduced delay experienced by road users. Capacity improvements from AVs are expected to be realized in different ways on controlled-access freeways and arterial streets because arterial streets have a much higher number of potential conflict points compared to freeways. In all cases, reduced headways between vehicles and near-constant speeds will enable more reliable travel times, which are a key influence for trip generation, timing, and routing decisions (Fagnant & Kockelman, 2015).

Freeway Capacity

For controlled-access freeways, lane capacity is largely a function of inter-vehicle spacing. AVs can enable a much higher utilization of roadway space than is currently achievable with human-driven vehicles (Pinjari, Augustin, & Menon, 2013). With sophisticated sensors, AVs will have significantly reduced reaction times compared to human drivers, and connectivity can effectively reduce the reaction time to zero, as vehicles will have perfect knowledge of the behavior of nearby vehicles.

Through precise control of acceleration to maintain close inter-vehicle spacing, AVs are expected to eliminate human error in driving. According to the NHTSA (2015), human error is the predominant cause of traffic crashes, responsible for 94% of incidents. Furthermore, the FHWA attributes 25% of traffic congestion to incidents including crashes and vehicle breakdown (Cambride Systematics, 2004). AVs have the potential to notably reduce the primary cause behind nearly one quarter of congestion.

There has been considerable research into quantifying the capacity improvement benefits of AVs in mixed traffic streams consisting of AVs and human-driven vehicles. Researchers have modelled AV performance in several ways based on different assumptions about the future of AV technology.

Yokota et al. (1998) investigate traffic efficiency improvements resulting from adaptive cruise control (ACC), which automatically adjusts a vehicle's speed to maintain a safe following distance, and proposed a model for capacity enhancement as a function of the proportion of ACC-enabled vehicles on the road. The lane capacity in a mixed traffic scenario can be determined according to Equation 1.

$$Q = \frac{3,600}{h_{ACC}P_{ACC} + h_{manual}(1 - P_{ACC})} \tag{1}$$

where Q is the roadway capacity in passenger cars per hour per lane (pcphpl), h_{ACC} is the average target headway of ACC-enabled vehicles (seconds), h_{manual} is the average headway of manually-driven vehicles (seconds), and P_{ACC} is the proportion of ACC-enabled vehicles in the traffic stream. The model assumes that each ACC-enabled vehicle maintains the target headway regardless of whether the preceding vehicle has ACC or not, which would likely require communication between vehicles to ensure safety, in the form of cooperative adaptive cruise control (CACC): enhanced ACC in a connected vehicle (CV) environment.

Shladover et al. (2012) examine the implications of ACC/CACC technology on highway capacity through microsimulation. The study assesses the capacity of a simple freeway section with varying market penetrations of vehicles equipped with ACC and CACC. The distribution of headways implemented in the simulation for each technology is based on user preferences from real world driving experiments. The study finds that ACC vehicles offer negligible capacity benefits (maximum 7%) because drivers tend to select time gap settings similar to the time gaps they adopt when driving manually. CACC vehicles are found to effectively double highway capacity at 100% market penetration (98% increase in lane capacity).

Tientrakool et al. (2011) investigate highway capacity benefits from the perspective of the capabilities of specific AV technologies. They find that semi-autonomous vehicles equipped with sensors for automatic braking could increase highway capacity by up to 40% at full market penetration. The combination of sensors with vehicle-to-vehicle (V2V) communication for automatic braking is found to increase capacity by 273%.

Arterial Street Capacity

Compared to controlled-access freeways, arterial streets in urban areas represent a more challenging environment for AVs due to the multitude of road users, signs, signals, and potential conflict points. Intersections are a key source of delay for manually-driven vehicles. CV technology has the potential to better optimize signal timing and minimize intersection delay, particularly in low to medium volume scenarios outside of peak hours. Goodall et al. (2013) develop a dynamic traffic signal control algorithm assuming the availability of position, heading, and speed data from connected vehicles and find that the algorithm maintains or improves performance compared with state-of-the-practice coordinated actuated timing plans at low and medium volumes. Dresner and Stone (2008) propose a more radical reservation-based approach to intersection management to replace the need for traffic signaling devices. The study shows that a reservation-based system to interchange management can minimize delay substantially (less than 3 seconds of delay on average, even at high traffic levels) when more than 90% of vehicles are fully autonomous. Even without an overhaul to the traditional traffic control system, shorter headways between vehicles at traffic signals and shorter start-up times mean that AVs could more effectively utilize green time at signals, improving intersection capacity (Fagnant & Kockelman, 2015).

Levin et al. (2016) simulate AV operations in downtown Austin, Texas using dynamic traffic assignment. They find that greater capacity on arterial streets results in a 51% reduction in travel time. With reservation-based intersection control, travel time reduction is found to be 78%. In some cases reservations disrupt signal progression, leading to queue spillback on arterial routes.

Since delays on arterial roads emerge largely from conflicting turning movements and pedestrians that AV technology cannot address easily, arterial congestion benefits are expected to be lower than for freeways. Fagnant (2014) estimates congestion benefits to be 5, 10, and 15% at the 10, 50, and 90% market penetration levels, respectively.

Impact of AVs on Vehicle-Kilometers Travelled

In the long-term, the value of lost time while travelling will be reduced by AVs because previously unproductive driving time can be used for productive activities. In general, AVs are more likely than not to lead towards more Vehicle-Kilometers Travelled (VKT). This can be attributed to changing parking patterns as well as through the provision of mobility to those currently unable to drive (Fagnant, 2014).

Activity-based simulations of AV adoption in the Seattle region examine various combinations of capacity increases, valuing travel time less than the typical value of time (to account for productivity while commuting), and reduced parking costs. These simulated scenarios result in a 4 to 20% increase in VKT (Childress, et al., 2014). Fagnant and Kockelman (2015) perform analysis assuming VKT per AV to be 20, 15, and 10% higher at 10, 50, and 90% market penetrations, respectively, reflecting the idea that “early adopters will have more pent-up demand for such vehicles than later buyers”.

METHODOLOGY

Simulations are conducted using Emme 4, a travel demand modelling software, in order to assess network performance on a regional scale in response to AV operating scenarios. Specifically, trips beginning during the AM peak period, 6:30 am to 9:29 am, are assigned to the GTA transportation network under various AV operating scenarios. The 2011 GTA base network, developed at the University of Toronto and widely used for trip assignment and planning studies, consists of about 2,000 traffic analysis zones (TAZs).

Emme performs static user equilibrium assignment of auto traffic to the network. Each link has an associated volume delay function (VDF), which relates the congested travel time to the volume-to-capacity ratio of the link. Equations 2 and 3 show the form of the tangent function VDF coded in Emme.

$$t = t_f\left(1+\left(\frac{V}{C}\right)^{\beta}\right) \text{ when } \frac{V}{C} \le 1.0 \qquad (2)$$

$$t = t_f\left(6\times\frac{V}{C}-4\right) \text{ when } \frac{V}{C} > 1.0 \qquad (3)$$

where t is the congested travel time, t_f is the uncongested (free-flow) travel time, V is the traffic volume on the link, C is the base capacity of the link, and β is a parameter. In the GTA Emme network, β is typically 6 on freeways and 4 on other roads.

Data

Trip distribution data for the GTA are extracted from the 2011 Transportation Tomorrow Survey (TTS), a comprehensive travel survey of the Greater Toronto Area (Transportation Information Steeting Committee, 2011). TTS survey data are modified via expansion factors to represent travel demand for all residents in the region. This study uses travel demand data for the auto drive mode, representing all travel by personal vehicles on an average weekday. Note that this methodology assumes that AVs will be used as personal vehicles and ignores the potential for AVs to act as autonomous taxis or enable dynamic ride sharing, for example. More broadly, this paper does not account for mode shifts that might occur as a result of AV adoption. Analysis is performed for several AM peak period scenarios, while auto assignment in Emme is performed for the peak hour. Conversion between peak period and peak hour demand can be done using a peak hour factor (PHF), which is calculated as 0.447 for auto trips in the GTA, based on TTS survey data.

AV Operating Scenarios

Modelling Capacity Benefits

Modifications to the base capacity of the road network listed in Table 1 are implemented in Emme to simulate several AV operating scenarios. The base capacity changes for freeways are based on the results of Shladover et al. (2012) and are applied for this investigation because they represent a comfortable middle ground, reflecting how drivers are likely to prefer using AV technology in the short- to medium-term following widespread adoption. The simulated capacity increases for non-freeway routes is lower than for freeways at higher levels of market penetration as delays are largely the result of conflicting turning movements and the presence of other road users (Fagnant, 2014). These congestion-inducing conflicts are difficult for AV technology to manage, without automated intersection management and complete (or near-complete) adoption of AVs (Dresner & Stone, 2008).

Table 1. Simulated Increases to Road Network Base Capacities

Network modification	Market penetration	Scenario A1: Restricted AV operations on freeways only	Scenario A2: General AV operations on all routes	Scenario B1: Restricted AV operations, with additional demand	Scenario B2: General AV operations, with additional demand
Increase to base	10%	+3%	+3%	+3%	+3%
capacity:	50%	+21%	+21%	+21%	+21%
Freeways	90%	+80%	+80%	+80%	+80%
Increase to base	10%	—	+5%	—	+5%
capacity:	50%	—	+10%	—	+10%
Non-freeway	90%	—	+15%	—	+15%
	10%	—	—	+2.0%	+2.0%
Increase in VKT	50%	—	—	+7.5%	+7.5%
	90%	—	—	+9.0%	+9.0%

"—"= no increase

Scenario A1 simulates hypothesized capacity benefits on controlled-access freeways only. This scenario reflects potential operational restrictions that might be legislated in the transition period before complete adoption of fully autonomous vehicles. Even with fairly widespread adoption of AVs, governments could prohibit use of AVs on arterial and minor routes over safety concerns related to conflict with non-motorized vehicles. Scenario A2 is a modification to Scenario A1, with the addition of hypothesized capacity increases on non-freeways.

Scenarios B1 and B2 hypothesize increases in VKT due to the adoption of AVs based on the work of Fagnant and Kockelman (2015), who project that VKT per autonomous vehicle will increase by 20, 15, and 10% for 10, 50, and 90% market penetrations, respectively. This increase in VKT is modelled in Scenarios B1 and B2 by assuming additional travel (and hence AV ownership) is distributed equally over the entire trip-making population. Thus the VKT increase is modelled by assuming a 2, 7.5, and 9% increase in trips for all origin-destination pairs at 10, 50, and 90% market penetration, respectively.

Measures of Effectiveness

The following measures of effectiveness (MOEs) are extracted from the Emme simulations in order to compare scenarios and evaluate the impact of AVs on the GTA's transportation network:

- change in average auto travel time for all trips;
- change in average auto travel time for trips involving freeways;
- change in average trip length; and
- change in percentage of trips involving travel on freeways.

In most cases, MOEs are compared relative to a base case assignment. The base case assignment is performed with the 2011 AM peak hour travel demand matrix and with no changes to any network capacities.

RESULTS AND DISCUSSION

Transportation System Performance with AV Capacity Benefits

Model results related to congestion benefits under AV operating scenarios are summarized in Table 2. In Scenario A1 (restricted AV operations on freeways only), average travel time savings at the 90% market penetration level are 21% for trips involving freeways (7.1 minutes) and 16% for all trips (3.0 minutes). On average, trips involving freeway travel are about twice as long as the average for all trips, hence the significantly higher absolute time savings for travelers using freeways.

Table 2. Summary of Travel Time and VKT Changes for Scenarios A1, A2, B1, and B2

Scenario	AV market penetration	Average travel time, all trips (min)	Percent difference in travel time, all trips	Average trip length, all trips (km)	Percentage of trips involving freeway travel	Average travel time, freeway trips (min)	Percent difference in travel time, freeway trips
Base Case	0%	18.54	0% (reference)	16.04	34.0%	34.26	0% (reference)
Scenario A1: Restricted AV operations on freeways only	10%	18.28	-1.4%	16.05	34.4%	33.27	-2.9%
	50%	17.35	-6.5%	16.10	35.8%	31.06	-9.3%
	90%	15.52	-16.3%	16.27	39.2%	26.43	-22.9%
Scenario A2: General AV operations on all routes	10%	17.90	-3.5%	16.03	34.3%	32.58	-4.9%
	50%	16.70	-9.9%	16.05	35.8%	29.90	-12.7%
	90%	14.92	-19.5%	16.21	39.6%	25.56	-25.4%
Scenario B1: Restricted AV operations, with additional demand	10%	18.63	+0.5%	16.06	34.2%	33.98	-0.8%
	50%	18.41	-0.7%	16.12	35.3%	33.17	-3.2%
	90%	16.37	-11.7%	16.28	38.4%	28.39	-17.1%
Scenario B2: General AV operations, with additional demand	10%	18.22	-1.8%	16.03	34.1%	33.18	-3.2%
	50%	17.60	-5.1%	16.06	35.1%	31.76	-7.3%
	90%	15.59	-15.9%	16.21	38.7%	26.96	-21.3%

In Scenarios A1 and A2, as well as in the base case, 891,000 trips are assigned to the Emme network for the AM peak hour. Approximately one-third of those trips involve travel on at least one freeway link. In Scenario A1 (restricted AV operations on freeways only), the proportion of trips involving freeway travel varies slightly with AV market penetration, indicating that a higher capacity increase on freeway relative to non-freeway links induces trip makers to modify their routes in order to access higher capacity freeway links. In the base case, 34% of trips involve freeway travel, while at the 90% AV market penetration level, 39% of trips involve freeway travel.

From the perspective of overall transportation system performance, a key issue emerges in modelling AV operations on freeways only (Scenario A1). If AV operation is not permitted on all routes, increased congestion is observed at freeway exit ramps and freeway-to-freeway connectors, and nearby arterials are not able to accommodate the increased throughput from the freeway at certain locations. Figure 1 shows locations in the Toronto downtown core where travel times increase due to additional congestion at heavily-used exits from the Gardiner Expressway and Don Valley Parkway.

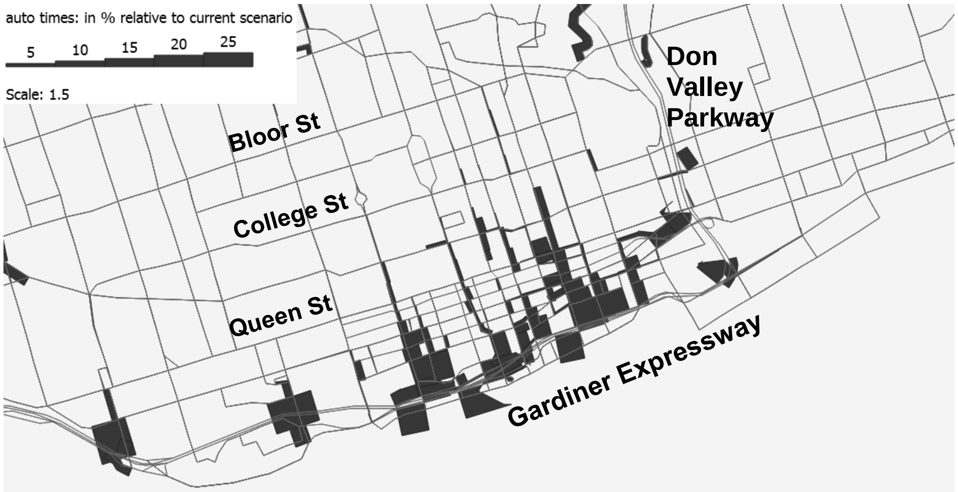

Figure 1. Scenario A1 (restricted AV operations on freeways only) with 90% market penetration. Grey bars indicate road links in downtown Toronto with increased travel time relative to the base case.

In Scenario A2 (general AV operations on all routes), average travel time savings at the 90% market penetration level are approximately 20% (3.6 minutes) for all trips, similar to the savings realized for freeway travelers in Scenario A1. Relative to Scenario A1, slightly fewer trips involve freeway travel, as more trips can be accommodated on the local road network, thus reducing the number of vehicles that divert to higher capacity freeways.

Scenarios B1 and B2 replicate Scenarios A1 and A2, respectively, but include hypothesized additional travel by AVs, distributed equally over the entire trip-making population (with the AM peak hour origin-destination travel demand matrix multiplied by a constant factor for each AV market penetration level). In Scenario B1 (restricted AV operations on freeways only, with additional demand), travel time savings are lower than were observed in Scenario A1 (restricted AV operations on freeways only). Savings are negligible at the 50% market penetration level, and the average travel time increases at the 10% market penetration level, illustrating that congestion benefits from AV-enabled capacity gains can be easily offset with even a modest amount of additional demand for travel. Specifically, the simulation results show that at the 50% market penetration level, a 7.5% increase in demand for travel essentially eliminates the benefit of a 21% increase in freeway base capacity. At the 90% market penetration level, savings are 12% on average for all trips, and 15% for trips involving freeway travel. In Scenario B2 (general AV operations on all routes, with additional demand), average travel time savings are 2, 5, and 16% at the 10, 50, and 90% market penetration levels, respectively. Relative to Scenario A2 (general AV operations on all routes), the results show that the inclusion of additional demand offsets about one-quarter to one-third of the travel time savings realized by modelling AV capacity benefits on the entire road network.

Valuing Travel Time Savings

Travel time savings can be quantified in monetary terms by linking the value of time to prevailing wages, in accordance with a standard method prescribed by the U.S. Department of Transportation (2014). Home-based trips, regardless of whether they are commuting trips or not, are considered personal trips and are valued at 50% of the hourly median wage, calculated from household income, assuming 2,080 work hours per year. Based on the median wage for the Toronto Census Metropolitan Area, travel time savings can be valued at $16.76 (2011 Canadian dollars) per hour (Statistics Canada, 2011). For Scenario A2 (general AV operations on all routes) at the 90% market penetration level, the estimated value of travel time savings for all auto drivers in the AM peak hour (for a single day) is CAD$901 thousand. On an annual basis, the value of travel time savings for all auto drivers in the AM peak period (assuming 252 working days per year with a PHF of 0.447) is approximately CAD$508 million. To determine the 24-hour annual value of travel time savings would require more extensive simulation throughout the day, as congestion exhibits significant diurnal variation. However, it is likely that the 24-hour annual value would be on the order of 2 to 2.5 times the AM peak period annual value, with similar benefits likely to be observed in the PM peak period, and some additional benefits outside of the peak periods.

Implications for Vehicle-Kilometers Travelled

VKT is an important metric by which to assess relative differences between AV operating scenarios. From a policy perspective, the majority of transportation planning agencies in large, developed cities seek to minimize VKT for a variety of reasons. In particular, modern planning practice typically seeks to realize the societal benefits that come from reducing transportation-related emissions, which are closely tied to VKT. Figure 2 shows the percentage change in average trip length for the first four scenarios. At the 90% market penetration level in Scenario B1 (restricted AV operations on freeways only, with additional demand), the average trip length increases by 1.5% relative to the base case, as vehicles divert longer distances in order to access higher capacity routes. In Scenario B2 (general AV operations on all routes, with additional demand), the increase is slightly lower but still non-zero because freeways are modelled to have a higher relative increase in capacity than non-freeway links at the 90% market penetration level.

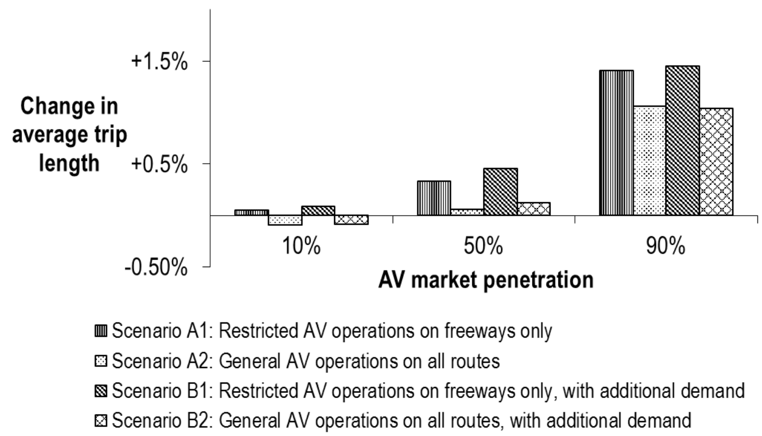

Figure 2. Percentage change in average trip length for all auto trips, AM peak hour.

CONCLUSION

Under optimal conditions, significant societal benefits might be realized through the widespread adoption of AVs, including reduced congestion, fewer collisions, reduced fuel consumption, enhanced safety for other road users, and providing drivers with additional time for economically-productive or leisurely tasks. On the other hand, AVs might also induce additional travel, increasing vehicle-kilometers travelled and negating congestion benefits. This paper focusses on the potential freeway and non-freeway congestion benefits of AVs. These benefits are due to the fact that AVs do not depend on human reaction time and are able to drive in a more foresighted manner compared to human drivers.

The increased attractiveness of freeway routes relative to others under AV operating scenarios is likely to be of particular concern to transportation planning agencies, which typically try to encourage a reduction in vehicular travel demand and VKT. The simulation results indicate that average trip length increases by up to 1.5% at 90% market penetration (without considering additional or induced demand). While the results show small increases in average trip length, significant travel time savings are realized. These savings are on the order of 1 to 7% at the 50% market penetration level and 12 to 21% at the 90% market penetration level, depending on restrictions placed on AV operations and on assumptions related to additional demand for travel by AVs.

Two scenarios model the effect of additional demand for travel by AVs. The inclusion of that extra demand represents a relatively conservative assumption as it does not account for demand that might be induced if travel times are reduced. The scale of the savings at high market penetration is similar to the effect of adding multiple lanes to major routes and so the "fundamental law of road congestion" could mean that all congestion benefits are offset by induced travel. Developed by Duranton and Turner (2011), the law states that VKT increases proportionally with roadway lane kilometers for highways and slightly less rapidly for other types of roads. The law could be adapted to account for capacity benefits that accrue due to the enhanced performance of AVs relative to human drivers.

Future research related to this work could involve investigating the influence of: induced demand for travel, alternative traffic assignment methods, alternative equilibrium assumptions, and using models of other urban centers.

Ultimately, the results presented here represent several possible future scenarios. The intention is not to suggest that any of these scenarios are certain, but rather to explore some of the possible implications of the widespread adoption of autonomous vehicles for personal travel. There are many questions that remain to be resolved, within the field of transportation engineering and in the fields of public policy, urban planning, manufacturing, and software design.

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