Emerging vehicle technologies & the search for urban mobility solutions

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ABSTRACT
The convergence of the ongoing innovations to make vehicles driverless, carbon free and accessible on ‘as needed’ basis, is evolving fast. A review of available information suggests that these technologies have substantial potential to generate positive externalities by improving road safety, lowering of fuel consumption and emissions in vehicles, and providing mobility options for vulnerable population including young, old and persons with disability. However, given the limited commercialization it is difficult to discern the nature of impact these technologies will have in reducing the two negative travel externalities, road congestion and low density expansion of cities. Gradual mainstreaming of these technologies will offer opportunities for further research in understanding the behavioral responses of their end users, and the risks that these technologies may pose to manufacturers, consumers, and stakeholders.

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Introduction
Over the past century human ingenuity has radically transformed our mobility choices with the advent of modes powered by fossil fuels. Cities, the hubs of human interactions and exchanges of goods and services, have prospered with the adoption of faster, cleaner and safer modes, and the provision of supporting infrastructure and services. The first car which rolled out 111 years back has incrementally undergone changes in terms of both increased comfort and safety. But the coming years is likely to bring radical changes in motorized vehicles and their use with significant impact on our mobility choices and governing legal and social norms (RAND Corporation, 2014). Broadly, the ongoing innovations are focusing on three key dimensions of vehicle technologies and their use.

The first innovation will make a car driverless by allowing robots to fully take over a driver’s chores or partially automate under a driver’s control. Driverless vehicles, known as autonomous vehicles (AVs), are undergoing trial tests in many countries. Some of the technologies that can substitute certain functions of a driver such as lane keeping, collision avoidance and parking, are already available in the market and used by new luxury cars. These vehicles are known as semi-autonomous vehicles. The second innovation will decarbonize vehicle fuel and improve fuel efficiency of vehicles. With the increasing concern for
climate change, air pollution and energy security there has been steady development in using new sources of low carbon fuel in vehicles. Finally, the third innovation will enable access to transport modes on an ‘as needed’ basis. The mobility option for using various forms of on-demand shared ride has always been with us but it is evolving fast with the application of emerging IT technologies and business practices.

Interestingly, all three innovations are for the same market place. Over time, they will merge together and begin to offer a unique set of new mobility options. Given the varying pace of development and many unknowns, it is difficult to predict how they will affect the main concerns of travel mobility – road safety, traffic congestion, energy use, green house gases (GHG) emissions and ultimately the built environment of cities. Will they enhance overall welfare of a society? To examine this question this paper summarizes the available information on the above three areas of innovations and identifies their externalities which will influence policy-making and the likely debate over their adoption in both developed and developing world societies. Because these technologies are still undergoing test runs, the paper identifies the potential benefits and risks of externalities as purely indicative of their nature and scale. Future mainstreaming of the above technologies in new vehicles will open opportunities for further research to precisely estimate the costs and benefits of these technologies, as well as their distribution between public and private segments of a society.

**Landscape of emerging vehicle based technologies**

**Autonomous vehicles**

It may sound like fiction but the reality of traveling on robots is here now. A driverless vehicle, called autonomous vehicle, equipped with radars, cameras, sensors and equipment for communication, algorithm computations and mapping are able to steer, keep the vehicle within its lane, maintain safe distance from vehicles ahead, automatically use breaks, facilitate parking, read the road signs and talk to other vehicles. A fleet of Google cars has already completed almost one million miles since the project started. Currently their cars are running in Mountain View California roads at a neighborhood-friendly speed of 25 mph (Ziegler, 2015). Similarly, Daimler, which owns Freightliner trucks, has completed 10,000 miles of test runs and is now introducing its trucks in Nevada State (O’Kane, 2015). Daimler intends for the autonomous features to solve the problem of fatigued driving, a major cause of crashes, rather than for replacing drivers. Ford is proposing to introduce the vehicle repositioning feature to move vehicles to a desired location by a remote driver, a kind of remote valet service. Numerous trials with the backing of governments and companies such as Volvo, Mercedes, Ford, GM, Tata/Jaguar/Land Rover and others are ongoing in various US and European cities. The semi-autonomous vehicles are those that offer features to substitute certain functions of a driver such as parking, cruise control, lane keeping, avoidance of front collision, etc. These features are already available in several new luxury cars like Tesla model S and Volvo XC60. Recently ten automakers in US have agreed to install standard automatic braking systems to avoid potential collisions in new cars (NY Times, 2015, September12). Even for old cars many car accessory companies (e.g. Mobileye 660) are offering add-on devices to assist drivers with lane departing, collision, pedestrian warning, high beam control and traffic sign recognition. Thus, the goal to reach complete
automation of vehicles with supporting roadside sensors does not seem too far, perhaps another 20 years or less.

**De-carbonized vehicles**

Over years, significant effort has been devoted to make our travel carbon free. The technologies to *de-carbonize vehicles* focus on improving fuel efficiency and/or fuel quality (other than fossil fuel or less carbon fuels). By reducing size, weight and vehicle’s air friction accompanied by improved design of internal combustion engines the new vehicles are steadily increasing their gas mileage. The new engines accept low GHG emission alternative fuels such as biofuels, compressed natural gas and liquefied petroleum gas. The fuel-cell vehicles use compressed hydrogen and oxygen from air to charge its electric motor and produce no tail pipe pollutants. This technology is tested and developed for cars (Toyota Mirai, Huyndai ix35 FCEV, many others), buses (Daimler AG, Brazilian Hydrogen), motorcycles and boats. But its adoption has been low due to the absence of hydrogen charging stations. On the other hand, the vehicles with hybrid drive-train technology (Prius, Honda and Ford Fusion etc.) generate their own electricity from the stop-and-go movements using regenerative brakes to complement the use of conventional fuels. The purely plug-in electric vehicles, E-mobility or EVs (e.g. cars like Nissan Leaf, e-buses, e-scooters, e-rickshaws and e-skate boards), reduce fuel cost by using electricity instead of conventional fuel. They can drive up to 100 miles consuming only 25–40 Kwh (U.S. Dept. of Energy [DOE], 2015a). But the EVs use has so far been constrained due to their limited range or maximum distance attainable after each battery charging (70–100 miles with few models longer), time required for battery charging (20 min to 20 h depending on technologies of charging stations, vehicles and batteries) and non-availability of battery charging or swapping stations similar to the gas stations (US DOE, 2015b). To a varying degree vehicles powered with each of the above technologies are already marketed by popular brands of auto manufacturers. Moreover, these technologies are undergoing further development to scale-up their adoption.

**On-demand vehicles**

The third area of innovations is largely based on the principal of sharing by connecting riders with drivers or the places to pick up vehicles (McKinsey & Co., 2015). The three key information technologies, GPS navigational device, smartphones and social networks, facilitate the process. For the real-time matching of drivers and riders an optimization algorithm takes the ride request from a smartphone call, uses GPS device to determine the location of the request and instantly provides route to the nearest available driver or vehicle pick up station (Rayle, Shaheen, Chan, Dai, & Cervero, 2014). The above coordination is complemented by social networks software to nurture trust and accountability between drivers and riders. This process of on-demand access with minor variations allows sharing of cars, scooters, bikes and even rickshaws in some countries. For modes stored at various locations, IT and other technologies (e.g. payment features) facilitate transactions of checking out and returning of vehicles (e.g. Zipcar, bike sharing programs of US and EU large cities). To facilitate car and mini-bus sharing there has been proliferation of ride sourcing companies like Zipcar, Uber, Lyft, Sidecar, Hailo, and Loup (a shuttle based ride service) and the list keeps growing across the world now. Around the world informal on-demand
services have been quite common but the emerging apps-based real time ride sharing and taxi services, like Ola, Meru (taxi hailing firms in India) and many others, are experiencing unprecedented expansion. They are building on-line communities and serving a variety of mobility needs. For instance, services like HopSkipDrive and Shuddle in California meet mobility needs of children on-demand basis with a click on a smartphone, and are useful for families without full time nannies, stay at home parents caring for more than one child, and divorced parents. HopSkipDrive requires drivers to have five years of child care experience and a clean background, and it monitors their driving records. Similarly, Priyadarshini, an on-demand taxi hailing service in Mumbai, caters to the needs of woman only and offers safe services around clock. These firms provide apps to its members and outsource rides to commercial drivers, or use their own fleet of vehicles to serve their members.

**Potential benefits of new technologies**

Considering the three paths of innovation presented in the earlier section, it is evident that these paths are developing interdependent technologies for a market place which is extremely varied and dynamic across countries and cities. To meet the evolving needs of each urban travel market, these technologies will ultimately merge together and offer market segment-specific services. The core technologies for doing so are already in the market. And they will steadily mature considering the ongoing R&D effort. Global auto industry is spending over $100 billion each year toward the advancement of autonomous vehicle development. However, the adoption of these developments will hinge on the question – will these innovations produce substantial social welfare gains in terms of improved road safety, reduced dependence on oil and resources, offer access to majority including the young, old and underprivileged, and promote efficient use of urban land? We will look for available answers to this question below.

**Improved road safety**

Under normal circumstances both the autonomous and semi-autonomous vehicles hold potential to eliminate millions of vehicle crashes. Even when a driverless vehicle experiences some kind of system failure the vehicle automatically yields to a safe mode operation, and in the case of semi-autonomous vehicle it will ask the driver to take control of it. Therefore, given the global estimate of 1.24 million annual deaths in vehicle accidents by the WHO (2013) the potential for reducing road deaths and accidents could be substantial. The largest beneficiaries of the above technologies will be mid-income countries where almost 52% of global vehicles are presently registered and their numbers are growing fast. Moreover, these countries are currently suffering with the highest rate of road fatalities, above 20 per 100,000 people, and had collectively shared 80% of worldwide road deaths in 2013 (see Table 1). Vulnerable road users (combined pedestrians, motorcyclists and bicyclists) represent more than half of the traffic deaths in low and mid-income countries. Since estimated value of statistical human life to per capita GDP could vary between 42 and 86 (iRAP, 2000) among countries the potential for reducing economic loss from purely road fatalities excluding the property damages, injuries, medical and other expenses, would be extremely high. And it will steadily rise with the future prosperity of countries and their population.
In US alone where almost 25% of global personal vehicles are registered, traffic accidents caused over 32,700 fatalities in 2013. With 90% of accidents caused by driver errors, total conversion of current fleet with autonomous vehicles could produce an annual savings of $563 billion (Lewis, 2014). Between 1991 and 2001 EU countries had reduced road fatalities by 30% with the application of intelligent safety systems that helped reduce driver errors (Forrest & Konca, 2007). Similarly, the US roadway crashes per million vehicle miles travel (VMT) fell at an annual average rate 2.3% between 1990 and 2011. The adoption of new technologies could further accelerate the downward trend of accidents in Europe and US. But the pace of change will largely depend upon the market penetration of new vehicles and retrofitting of current vehicles with new safety features to avoid collisions. As per a US study (IIHS, 2012) it typically took almost three decades for a promising safety feature (e.g. seat belt, air bags) to spread through the fleet and reach say 95% of vehicles. In this respect the developing countries with low level of motorization will have the opportunity to leap frog in adopting collision avoidance technologies. Besides lowered road crashes linked savings countries would reduce insurance payments, vehicle maintenance and repairs, costs incurred in emergency rooms, general hospitalization and the burden of law enforcement. Already the frequency of property damage liability claims and body injury liabilities have declined by quarter in new cars with collision avoidance features such as Volvo XC60, compared to similar SUVs without it (IIHS, 2012). Thus it is safe to say that road safety linked social welfare gains from the increased adoption of these technologies will be significant in the coming decades. Moreover, with steady decline in prices of these technologies and increasing awareness about potential savings low and middle income countries will benefit the most given the prevailing high rates of traffic accidents in them.

### Low energy use and emissions

The future transport system promises to reduce fuel consumption by improving efficiency in driving and better design of engines and vehicles. With platooning of automated or semi-autonomous vehicles potential for overall throughput of roads, bridges and tunnels will increase, and loss of energy in acceleration and deceleration will be further reduced. Today’s cars are able to attain up to 20–30% fuel saving under cruise control and smooth driving conditions. The aerodynamic body design promises to reduce the effective drag coefficient on vehicles, saving up to 20% fuel (KPMG, 2012). Moreover, future cars will be lighter as more and more vehicles become connected with features to avoid collisions. A weight reduction of 100 kg saves between 0.3 and 0.5 l per 100 km driven (European
Commission [EU], 2012). De-carbonization initiatives such as use of electric drive train will improve efficiency of energy use to 90% compared to 37% observed in gasoline engines. Additional benefits of emission reduction will come from increasing mix of renewable sources in power generation.

A study of 9500 participants of on-demand car sharing programs in US and Canada (Martin, Shaheen, & Lidicker, 2010; Shaheen & Chan, 2015) had found that each car sharing vehicle had replaced 9–13 vehicles among their members. The car sharing members had either sold a vehicle or postponed purchasing a vehicle. The reduction in number of personal vehicles can have a notable impact on reducing VMT and GHG emissions. Ride sharing with short wait time, flexibility in using them at any time and location and free of parking hassle for those used to driving personal cars has begun to lower household car ownership rate in large cities. Therefore, it is possible that the future fleet of automated, fuel efficient vehicles using more and more renewable energy, and popular use of on-demand vehicle sharing options will attain substantial savings in fuel use and resulting vehicle emissions.

However, according to researchers of University of Michigan Transport Center (UMTRI, 2015) autonomous vehicles may increase VMT but cut ownership of vehicles. Using the National Household Travel Survey data of US they indicate that the vehicle ownership may decline by 43% from 2.1 per household to 1.2 (UMTRI, 2015). Since a driverless vehicle can be returned to serve other household members instead of being parked at home or work place, the need for a second car will be minimized. But most US households undertake separate trips for adult commute, school trips and other errands which will increase passenger-less return-home trips by driverless cars. With the result the study estimates 75% increase in annual travel miles per vehicle, from 11,684 to 20,406 miles. Moreover, AV vehicles will also enhance mobility of disabled, children and old people. This raises the question – will the increased travel-linked fuel use and emissions be negated by the advances in vehicle efficiency and use of decarbonized fuel? Given the early stage of autonomous vehicle development, it is difficult to foresee the likely changes in traveler’s behavior, and how will they respond to the increased costs of undertaking multiple trips and congestion if any. The counter balancing effect of increased VMT and related costs on savings from reduced energy use, emissions and vehicle ownership will perhaps differ across countries.

**Reduced traffic delays**

Introduction of improved vehicle design and autonomous features promises to improve flow of traffic and minimize long delays linked to road crashes. As the number of autonomous vehicles in traffic mix will increase over time the benefits of steady traffic flow will be realized by its purchasers. Research has shown that vehicle platooning can improve road capacity by almost 500% (Fernandes, 2012). Since autonomous vehicles will know how to avoid conflicts, the need for many signals and signs will be eliminated. The simulations of intelligently controlled intersections, where approaching vehicles communicate with each other, have shown that they can perform many times better than traffic signal controlled intersections (Dresner & Stone, 2005). Bus and truck operators will gain immensely from smoother traffic flow and reduced congestion in terms of improved performance of their fleet and logistics services. Currently EU countries loose almost 1% of GDP in traffic congestion, while in US as per the 2015 Urban Mobility Report $160 billion was lost in combined delays and fuel costs in 2014 reflecting $916 per year for each commuter.
Moreover, one-fourth of delays on US roads are due to traffic incidences like vehicle collision and disabled or overturned vehicles (Federal Highway Administration [FHWA], 2013). Thus the benefits of new technologies in increasing throughput of roads could be substantial for a society and its road users by reducing overall cost of driving and minimizing accidents and congestion.

With increasing use of automated vehicles (AV) their drivers will have the opportunity to work within vehicle en route to work or meeting. The new vehicles are already coming with features to be connected through emails, messaging, web access, etc. The future autonomous vehicles may also provide flexibility in re-configuring the cabin for work or other needs. The question is how much productivity gain can be realized by a driver. People do work in trains or buses. A recent study by AT&T in US found that 61% of people admitted that they text while driving, 33% said they email and 27% said they use Facebook. No doubt these practices are causing many more accidents but they do reflect the increasing desire of drivers to communicate with others for work or non-work purposes. So for the sake of illustration if we assume that all current drive-alone car using commuters in US, 107 million (U.S. Census, 2013), will use 50% of their average 50-min commute time (two-way) productively in autonomous cars. Then total productivity gains can reach $788 million per year at an average value of time of $17.67 per hour, a value used by TTI (2015). The indicative figure is promising but subjective and may open some debate.

However, the reduced marginal cost of driving and driver’s productivity gains in using time spent in cars may encourage vehicle users to trade off these savings for longer drive and/or more trips. In such cases overall VMT may increase leading to more dispersed, low density land development. This phenomenon known as rebound effect, has been observed in many countries after improvements in vehicle fuel use efficiency and/or road capacity. For example, a US study had shown that 1% increase in fuel economy raised VMT by 0.2 to 0.4% (Linn, 2013). However, as per another study for US states the effect of fuel efficiency between 1966 and 2001 was found to diminish with rising income aided by falling fuel price (Small & Dender, 2007). The decline in rebound effect over time seems to be due to the increased congestion.

On the contrary, in the case of on-demand ride services users will be paying higher unit cost of trip (say, $ per mile including the cost of owning a vehicle and operation) compared to the out-of-pocket unit cost (gasoline, maintenance and tire) incurred by those using their own vehicle. With the result the propensity to use on-demand services will be lower among its users, and it would lead to overall reduction in VMT and road use. Given the feedback interactions among various behavioral responses discussed above there will be uncertainty in realizing the full benefit of efficient road use. And it will persist till further evidence-based researches are undertaken under varied conditions and levels of technology adoption.

**Compact urban development**

The arrival of driverless cars immediately raises a question in many minds – Are we increasing our love affair with cars? The fear of getting farther, faster and more frequently for fulfilling daily needs in cars is real. As discussed before the reduced cost of travel for users of autonomous and semi-autonomous vehicles may increase their willingness to travel longer from home to work. With the result cities will experience increased dispersal of their population and low density expansion in peri-urban areas. This phenomenon is already in
motion across the world cities with population growth, economic development and cheap travel. The recent findings of an urban expansion study of 120 cities suggest that the built area of cities expanded at an annual average rate of 3.6% while their population at a rate of 1.6%. With the result consumption of urban land per person in these cities increased at an annual rate of 2.1% (NYU, 2015; Shlomo, 2012). Hence, the concern about new vehicle technologies providing further inducement to the ongoing low density dispersal of population is real unless context-specific appropriate policies and measures are undertaken to promote a market-driven compact land development.

Most on-demand service and autonomous personal vehicles are likely to be in constant use to pick-up and drop-off people instead of sitting idle in parking lots. This will lead to reduced demand for parking spaces, particularly in central business district (CBD) of cities. This will create opportunities for in-fill high density development on land currently used for parking. The potential for central area densification is significant in many US cities where up to 31% CBD land are used for parking (Shoup, 2005). Similarly, in large metropolitan areas use of on-demand services will save gas miles that are often spent in search for parking spaces. A parking study for New York West Side estimated that motorists spent 366,000 miles per year, almost one way trip to moon, in search of metered parking in a 15-blocks stretch (Transportation Alternatives, 2008).

In developing world cities where public transport use is prevalent, the introduction of autonomous or semi-autonomous features in their public transport fleet and the last mile feeder services (buses, e-rickshaws etc.) to bus and train stops/stations would be highly beneficial. In these cities mobility providers may offer small, light, two sitter automated vehicles for short trips and as feeders to trunk public transport systems like BRTs and metro. By promoting public transport use, particularly in newly developed areas, cities will encourage consolidation of activities in the proximity of transit nodes and promote compact, mixed-use development. Higher density will further enhance opportunities for on-demand ridesharing and public transport use. Public transport would also attract new riders by providing IT-enabled on-time services and adjusting routes and vehicle scheduling to real-time demand and specific requests of riders (e.g. trip requests from old, persons with disability, etc.).

Therefore, the future shape of cities will be determined by the adopted land, technologies and modal development priorities and policies. In general, at first the price of vehicles with advanced technological features and AVs will be significantly higher than conventional vehicles. This will limit the pace of their adoption in most countries, and particularly in low-income countries. So the changes in urban-built environment density and structure will continue to be driven by the trend of motorization, availability of affordable and reliable public transport and para-transit services, and prevailing road travel conditions (time and cost of travel). The puzzle of discerning the nature of locational choices that will be made by users of new technologies will remain a challenge for every city official.

Table 2 summarizes the broad conclusions of the above discussion in terms of potential benefits that each attribute of the three emerging vehicle technologies will offer to a society.

**Potential benefits of automated vehicle use in Washington metro: an illustrative review**

To illustrate the potential benefits of automated vehicles use in the Washington Metro, an area of 5.4 million residents and ranked as number one among the US cities for congestion
delays (TTI, 2015), has been selected. Prior research (Jones & Phillips, 2013; van Arem, van Driel, & Visser, 2006) has identified that the positive impact of AV vehicles on flow stability and road capacity is likely to be visible only above 40% penetration of these vehicles in traffic stream. In light of this observation, our review assumes that Washington Metro will have above 40% share of AV vehicles with adaptive cruise control and vehicle-to-vehicle communication (V2V) in the next two and half decades. Since many key characteristics of AV technologies (e.g. acceleration and deceleration rates, permissible minimum headway, traffic flow behavior in mix and other traffic conditions) are neither known nor fully developed, the estimates of potential benefits discussed below are purely indicative and based on broad assumptions. For our analysis, the 2040 traffic forecast data published by the Metro Washington Council of Governments (MWCOG, 2015) and other secondary sources are used.

### Reduced traffic delays and related emissions

By 2040, traffic congestion in the Washington metro is expected to worsen further despite planned improvements in road and transit capacities (Table 3). During the morning peak the lane miles in congested conditions is projected to increase from 1728 to 2966 during 2015–2040. With the result almost one-third of regional VMT, 3.75 million miles, will be congested (i.e. road sections with volume/capacity ratio exceeding one). Congestion will be concentrated mostly along the highway corridors connecting the suburbs and the beltway of the city (see Figure 1). Although a similar picture of congestion exists today, it will substantially deteriorate due to the anticipated future growth of population and jobs in suburbs. By 2040 additional one million daily commuting trips will originate in suburbs, of which almost 80% will be using automobiles for travel to the planned regional activity centers.

As discussed earlier, the AV technologies promise to decrease the average safe inter-vehicle distance while maintaining 60–65 mph speed on freeways. In other words, the reduced headway between vehicles will increase the density of vehicles in a road section and the flow

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### Table 2. Potential social benefits of emerging vehicle technology attributes.

| Vehicle attributes     | Improved safety | Low energy & emissions | Reduced delays | Compact development | Mobility for vulnerable |
|------------------------|-----------------|------------------------|----------------|---------------------|------------------------|
| Decarbonized fuel       | N/A             | Positive               | Uncertain      | N/A                 | N/A                    |
| Fuel efficiency         | N/A             | Positive               | Uncertain      | Uncertain           | N/A                    |
| Semi-autonomous         | Positive        | Likely positive        | Uncertain      | Uncertain           | Positive               |
| Autonomous             | Positive        | Likely positive        | Uncertain      | Uncertain           | Positive               |
| On-demand service       | N/A             | Positive               | Likely positive| Likely positive     | Positive               |

### Table 3. Road congestion for the Washington Metro in 2040.

| Metro area    | Lane miles | Congested lane miles | Congested VMT ('000) |
|---------------|------------|----------------------|----------------------|
|               |            | %                    | Miles                | VMT | % | VMT  |
| Regional core | 2300       | 21                   | 483                  | 1269 | 37 | 470  |
| Inner suburb  | 9700       | 18                   | 1746                 | 6700 | 34 | 2278 |
| Outer suburb  | 6100       | 12                   | 732                  | 3331 | 29 | 966  |
| Total         | 18,100     | 16                   | 2961                 | 11,300 | 33 | 3714 |

Source: WASCOG – https://www.mwcog.org/clrp/performance/congestion.asp.
rate (vehicles per hour per lane) without dropping the traffic speed. With the technological advancement in sensors and V2V communication the new AV vehicles aim to reduce safe distance between vehicles (headway) up to 0.5 s without causing crashes at a high speed. But the technological changes and their rate of adoption will vary across cities over the coming decades. Hence, for the Washington Metro scenario we will assume a range of minimum headways and the likely level of AV market shares that may be attained by 2040.

To calculate the traffic flow rate under various levels of AVs and non-AV vehicles in an uninterrupted multi-lane road, the following equation is used (Yokata, Ueda, & Murata, 1998):

\[ Q_d = \frac{3600}{(H_{av} \times S + H_{manual} \times (1 - S))} \]

(1)
where \( Q_d \) = Average flow rate, vehicles/hour/lane; \( H_w \) = Headways for AVs; \( H_{\text{manual}} \) = Headways of manually driven vehicles; and \( S \) = Share of AVs in traffic stream (%).

A comparison between the calculated flow rates from Equation (1) and the observed flow rates from the prevailing speed–flow relationship for Washington area highways (Skycomp, Inc., 2011) suggests the likely changes in highway capacity that may occur with the introduction of AVs. Table 4 presents the calculated increases in highway capacity under varying traffic conditions and a range of AV headways and their market penetration rates. For instance, the capacity of highway sections operating at their capacity \( (V/C = 1) \) may increase by 3.3 times under 100% AV market penetration and 0.5 s headway. Such a jump in highway capacity seems high but consistent with the findings of a recent study (Trientrakool, Ho, & Maxemchuk, 2011) which has shown that at 65 mph (100 kmph) all vehicles equipped with both the collision avoiding sensors and V2V will be able to increase freeway capacity by 3.7 times but by 1.4 times if equipped with only sensors.

Broadly speaking, highway capacity increases between 1.4 and 3.3 times will substantially improve traffic flow and speed of Washington Metro highway network and produce significant savings in travel times for peak period AV users.

The Urban Mobility Report (TTI, 2015) indicates that in 2014 the congestion time loss was estimated to reach $3.6 billion in Washington Metro. For each auto commuter it represents an annual loss of 82 h and $1433. During the peak period average travel time for auto commuters was 34% higher than the travel time under free flow conditions, expressed as travel time index (TTI) in Table 5. The TTI value reflects an average measure of peak hour condition over the entire road network but the highly traveled corridors, such as the radial and beltway highways, experience above average severity of congestion. By 2040, the TTI value is expected to rise due to the addition of projected 0.58 million new auto commuters, an increase of 23% from 2015. For this analysis, it is assumed that the current average \( V/C \) ratio, 1.23, may increase at a rate similar to the auto commuter growth during 2015–2040. Using the following speed–flow relationship (BPR equation) for highways and the estimated \( V/C \) ratio, the average Metro level TTI (see Table 5) will reach 1.78. In other words, the average peak travel time in 2040 will be 33% higher than the 2015 figure.

\[
TTI = \frac{t}{t_0} = (1 + a(V/C))^b
\]  

(2)

where, \( t \) and \( t_0 \) are travel times during peak and free flow conditions, and \( a \) and \( b \) are assumed to be 0.15 and 4 respectively, a commonly used figures for highways in US.

By applying the same 33% increase to the 2015 delay hours per auto commuter, in 2040 the cost of delays per auto commuter (excluding the trucks and excess fuel use) will reach $1933 and $5.9 billion at the metro-wide level. According to the MWCOG travel forecast

### Table 4. Estimated highway capacity with increased share of AVs in traffic stream.

| LOS | Density (v/l/m) | Speed (mph) | Traffic flow (vph/l) | Headway (s) | Target headway (s) | Capacity in multiple of traffic flow |
|-----|----------------|-------------|---------------------|-------------|--------------------|-----------------------------------|
| E   | 39             | 55.8        | 2190                | 1.6         | 1.01               | 0.9                               |
|     |                |             |                     | 0.9         | 1.22               | 0.5                               |
| Capacity |                |             |                     | 1.6         | 1.01               | 1.01                              |
| V/C = 1 |                |             |                     | 1.3         | 1.01               | 1.02                              |

Source of speed flow relationship from Skycomp, Inc. (2011).
(MWCOG, 2015) the congested lane miles and VMT is anticipated to increase by 72 and 77% respectively during 2015–2040. Looking at such an increase in network congestion, the estimated 33% increase in TTI may be an acceptable figure though purely indicative for this illustration. For a more accurate estimate of the total time delays, a regional road network level traffic flow analysis for 2040 peak conditions need to be undertaken using the MWCOG models, an exercise which is beyond the scope of this paper. Although savings in fuel use and emissions will depend upon future efficiency and use of carbon free fuel, the reduction in delays by AVs introduction will definitely reduce emissions and excess fuel consumption. However, the latter benefit may be negated to some extent if AV users trade off the savings with more miles of travel.

The question – how much of the above-estimated $5.9 billion loss in time delays will be saved by the introduction of AVs in 2040 – will largely depend upon their market penetration rate, technologies permitting a level of minimum headway and V2V communication, and the emerging speed–flow relationships as observed under varying conditions including road categories and driving behavior. However, considering the above-discussed potential increases in road capacity with AVs, between 1.3 and above 3.7 times the current capacity, we can say that the Washington Metro can at the minimum stop increase in current level of congestion with about 30% improved road capacity. And under the 100% AV penetration scenario, the metro area will potentially fully eliminate congestion in 2040. For a more robust estimate of likely capacity increases and their impacts on traffic flow, one may undertake traffic simulations for each corridor using the road design features and assumed traffic flow parameters (e.g. mix of vehicles, minimum safe headways, acceleration and deceleration rates, etc.). Given the unknowns, many questions about future congestion and the contribution of AV will remain unanswered for years to come.

**Impact on development & mobility**

According to MWCOG study, the accessibility to jobs measured in terms of number of jobs within 45 min of auto travel will increase from 918,000 to 939,000 between 2015 and 2040. Such a small change, about 2%, is mainly due to the anticipated road congestion and concentration of new jobs in the western suburbs. Average accessibility by transit, though less than automobile, will increase by 36%, from 398,000 to 543,000 during the next 25 years. But the increased use of AVs in 2040 does hold great potential to ease congestion along major highway corridors and improve accessibility of car, truck and bus users. Under a

![Table 5. Cost of time losts due to congestion in 2014 and 2040.](image-url)
scenario of 30% improvement in road network capacity by 2040, Metro auto users will be able to access more jobs within 45 min. Moreover, overall auto and transit accessibility may also improve if future jobs and population growth occurs in inner suburbs and close to the planned activity centers. But a high market penetration of AVs may encourage further decentralization of population and activities beyond 2040 due to the enhance capacity and speed of travel.

According to the MWCOG, the changes in locations of jobs and traffic congestion within the Metro region will affect the auto accessibility of persons with disability in 2040. Overall there will be minor improvement, additional 18% of jobs (18,000) will be within 45 min for this group. But the incidence of accessibility will vary with 29% experiencing gain, 4% experiencing loss, and the rest 67% insignificantly impacted. The use of AVs by disabled population is likely to enhance the job accessibility due to reduced travel time, at the same time increase their participation in the regional job market. The 2000 Census Metro enumerates 0.7 million residents with disability, 15.2% of the 4.54 million population (MWCOG, 2015). Therefore, depending upon the anticipated population of elderly and disable persons out of the 6.6 million in 2040 overall welfare benefits of accessibility improvement could be significant for the vulnerable group.

**Benefits of reduced crashes**

AVs are expected to eliminate accidents caused by driver errors which are responsible for almost 90% of crashes in US. But to make AVs crash free, they must overcome non-human safety risks such as inclement weather conditions, road surface conditions, debris, and other risks posed by non-AV vehicles using roads including bicycles, and pedestrians. With increased perception of safety, AV users may drive at a higher speed and may also increase miles traveled. Therefore, it is difficult to foresee how safe driving will be in 2040 Washington Metro region. In 2009 the estimated cost of crashes was $7.46 billion, almost 84% higher than the cost of congestion the same year (Cambridge Systematics, 2011). Assuming the 2009 rate of fatalities and injuries per million persons in 2040, the cost of crashes will reach $9 billion (in 2009 dollars as shown in Table 6). In the next two and a half decades, most vehicles including the non-AVs are likely to have collision avoidance features. Thus, the overall reduction in crashes could be substantial, perhaps above 70–80% considering that the EU countries had reduced fatalities by 30% in a decade (1991–2001), and the US over 20% during 1951–1961. Therefore, by 2040 potential benefits of crash reduction may reach $7–8 billion in Washington Metro.

**Risks and challenges**

Although the potential benefits of the three emerging vehicle technologies are likely to be substantial they will pose several risks and philosophical issues. Our living and mobility patterns will undergo a major transformation, and it will be true for the businesses as well. The coming years will witness an accelerated pace of evolution and adoption of these technologies though it will greatly depend upon the way each society will manage their risks and challenges as highlighted below.
technology will enable driverless and safer future vehicles but dealing with the potential liabilities of these vehicles will impede their adoption and commercialization. Accidents will always be an aspect of vehicle use, and the liability questions that autonomous vehicles will raise are going to be important for governments, insurers, manufacturers and users. The question of ‘who to sue’ when an autonomous vehicle is involved in an accident raises many issues. For instance, if the accident is caused due to the defective vehicle or its component design then one may consider the framework of product liability law to address it (Villasenor, 2014). Under the law a car manufacturer will be liable for manufacturing defect, design defect, failure to meet warranty conditions and poor quality. But some of the times human interventions will be made in autonomous vehicles which will trigger the question of liability sharing between insurers and manufacturers. To determine the human error linked damage, an insurer will require access to data, the car’s ‘black box’ that could be used to reconstruct the actions that a driver and the software partially controlling the vehicle took in the moments preceding an accident. As the risks will begin to move toward the machine and away from the driver, the insurance industry will undergo major changes. The premiums have to be matched to exposure rather than based on proxies.

With declining car ownership in favor of on-demand ride sharing model and taxi companies, insurance practices will be geared toward vehicle fleet owners to provide company-wide policies. Thus, the liability management question is among the dominant concerns right now and a make-or-break issue for marketing autonomous vehicles. Countries are in the process of developing legislations to address liability concerns and designing comprehensive regulatory regime and safety standards. The safety standards have to be stringent enough to ensure that the fatality rates of autonomous vehicles are far below the rate under human drivers. Many states in US (California, Florida, Michigan, Nevada and DC) have already adopted legislations in this regard to initiate testing of new vehicle technologies. For instance, the Nevada state requires the purchaser of a vehicle to have a certificate of compliance for the autonomous technology installed in the vehicle by the manufacturer or an autonomous certificate facility market. The certificate issuing entity is required to pay a sum of $300 and a surety bond of $500,000 to allow operation of the vehicle (RAND Corporation, 2014). It is unclear what additional cost the certificate will impose on the end users. Unless the liability issue is comprehensively dealt with, manufactures will either delay introduction of new technologies or price them to incorporate their liability risk.

### Liabilities

Table 6. Cost of crashes in 2009 and estimated for 2040 without AVs.

| Type       | Number | Cost (mil) | Per mill. Pop. | Cost (mil) | Number |
|------------|--------|------------|----------------|------------|--------|
| Fatalities | 350    | $2100      | 64             | $2532      | 422    |
| Injuries   | 42,566 | $5363      | 7781           | $6471      | 51,355 |
| Total      | 42,916 | $7463      |                | $9003      |        |

Source: Cambridge Systematics (2011).
Ethical dilemmas

Autonomous vehicles will confront many ethical challenges particularly under scenarios like the one cited below and taken from a blog of Jason Millar, called the tunnel problem (Millar, 2014).

You are travelling along a single lane mountain road in an autonomous car that is fast approaching a narrow tunnel. Just before entering the tunnel a child attempts to run across the road but trips in the center of the lane effectively blocking the entrance to the tunnel. The car has but two options: hit and kill the child, or swerve into the wall on either side of the tunnel, thus killing you. How should the car react?

From a car design perspective the above problem raises two questions: how should a car be designed to react in difficult situation; and who should decide how the car must react? Such ethical issues are common in health care field like end-of-life decisions. As in health care, one may consider a driver’s preference to reflect his/her moral choices. Hence, car designers must seek explicit choices from the car users if they confront unavoidable crash scenarios. But how many such scenarios must be considered? Should one limit the scenarios to a few serious ones, if so what will be those? The example discussed here simply highlights the nature of ethical issues autonomous vehicles have to address before entering the general market.

Privacy

Although benefits of vehicle sensors, GPS and communication technologies are appealing they also face privacy concerns of individuals. The questions on how information is collected, archived and distributed are of importance to many who are concerned about the misuse of their personal information. People are demanding transparency from the data mining firms. It has become national concern in many countries. Regulators are struggling to address them with new regulations that will seek a right balance between the interests of society and its citizens.

Cybersecurity

Security threats from unauthorized parties, hackers or even terrorists will arise in the world dominated by autonomous vehicles. One can easily imagine the nefarious possibilities one watches in sci-fi movies. Recently two hackers showed how they can remotely take full control of a Jeep including its brakes, engines, GPS, air-conditioning and so on (Harkness, 2015). Similarly, a year ago Cesar Cerrudo, an Argentine security researcher, showed how he can hack the city’s traffic system from his laptop. He was able to gridlock the system by turning red light to green and green to red (NY Times, 2015). Recently, Chrysler has recalled 1.4 million cars that are equipped with certain radios which could be hacked. Although cybersecurity experts are busy designing security functions for hardware and software, the fear of getting hacked will persist for some time.
**Job loss**

With the popularity of autonomous vehicles and ride-sharing rental models, overall vehicle ownership may decline in the long term. If so then fewer gas stations, car repair shops, car dealers and insurance services will be necessary. Similarly, improved driver safety will reduce demand for hospital services and traffic enforcers. Historically, technological revolutions have caused short-term job loss but over time created more jobs although of a different nature. Nevertheless, the transition will be arduous. One can clearly note the recent protests in Europe, India and in many US cities against the introduction of Uber services even though it creates more jobs than it destroys. Uber is an example of disruptive innovations that brings increase in efficiency but opens up several regulatory challenges. The affected traditional taxi operators are demanding Uber to meet similar regulatory requirements including passenger insurance coverage, taxes, driver health and professional test, etc. However, the expansion of new vehicle technologies would create many new jobs in areas of logistics and delivery services, elderly support, software and hardware development and maintenance, customized vehicle designs, intelligent infrastructure development, etc.

**Conclusions**

The convergence of the three emerging vehicle technologies – driverless vehicles called Autonomous vehicles, carbon free efficient vehicles, and on-demand shared vehicles – is evolving fast with significant promise to improve overall social welfare. The transition has begun with partial application of new technologies under driver’s control (e.g. rear and front end collision avoidance, automatic parking, auto steering, etc.) in vehicles called semi-autonomous vehicles. The paper examines the potential benefits that each key attributes of these technologies will produce for the public in general and their users. Based on the available information and past experiences with the improvements in similar technological attributes, the paper concludes that these emerging technologies have substantial potential to generate positive externalities by improving road safety, lowering of fuel consumption and emissions in vehicles, and providing mobility options for vulnerable population including young, old and persons with disability. At the current state of knowledge, it is difficult to discern the nature of impact these technologies will have in reducing the two negative travel externalities, road congestion and low density expansion of cities. Gradual mainstreaming of these technologies will offer opportunities for further research in understanding the behavioral responses of their users, and the risks that these technologies may pose to manufacturers and consumers. The day when many fully and/or partially self-driven vehicles will be with us may not be far. But it will depend upon the pace at which the technologies will mature under a regulatory regime which will protect the end users, manufacturers and stake holders from the residual risks and liabilities of new technologies.

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