DECARBONISATION OF TRANSPORTATION:INSIGHTS INTO VEHICLE AUTONOMY, ELECTRIFICATION AND SHARING IMPLICATIONS FOR BRITISH COLUMBIA, CANADA[1]

Orhan Atabay, Curran Crawford and Ned Djilali

Introduction

Automated vehicles (AV's) perform various driving tasks without the control of a human operator, depending on their level of autonomy. The Society of Automotive Engineers (SAE) defines 6 levels of vehicle automation from "1=no automation" to "6=full autonomy" to categorize automated vehicles ("Automated Vehicles for Safety", n.d.). Automated vehicles of the future will also be connected vehicles (CV's) which can communicate with other vehicles in traffic, and surrounding infrastructure using predefined networks and protocols. Such information sharing provides benefits in terms of finding optimal driving patterns, conditions and routes.Shared vehicles (SV's) enablevarious types of vehicle operation resulting in a wide range oftransportation modes, aiming to reduce vehicle ownership rates and cost of vehicle km's travelled.In terms of electrified powertrain architectures, plug-in electric vehicles and plug-in hybrid electric vehicles (xEV's) employ diverse architectures, which make use of (renewable) electric energy from the grid.

Shared and automated vehicles (SAV's) are expected to have positive impacts in many areas. The most evident ones include: improved road safety (less collisions);less congestion (replacement of non-automated vehicles with less automated ones);better economy (mainly due to less collisions);increased productivity (less hours spent in traffic jams and ability to work in vehicles);greater accessibility to mobility (for younger people, seniors and people with special needs) (Harper et al. 2016);equitable land use (optimal traffic management, automated highway systems (AHS), platooning, decrease of number in parking spaces);lower cost of mobility (for individuals, families, communities, companies, governments);fewer barriers for public transit use (especially first and last mile barriers) and better fuel economy (optimal driving strategies and route planning) (Fagnant and Kockelman 2015, Wadud et al. 2016, Taiebat et al. 2018, Driving Change 2018).

On the other hand, there are concerns associated with the automation of road vehicles, such as:complexitiesin policy making (e.g.,testing on public roads, policy relations with insurance and liability and updates of traffic laws);uncertainties around public acceptance;resistance to adoption of such vehicles (especially related todemography and geography); alterations in the job market;decrease in governmental income (e.g., fees, taxes, traffic fines);increase in governmental expenses(e.g., infrastructure and services); unsecure data privacy and security of users; increased risks of cyber attacks; enormous data storage requirements and social inequity based on allocation of resources (e.g., special parking lots, lanes or areas for SAV's) (Fagnant and Kockelman 2015, Wadud et al. 2016, Taiebat et al. 2018, Driving Change 2018).

It can be expected that some of the factors mentioned above will result in less energy use and lowered GHG emissions, with different levels of contributions: less congestion, less collisions, optimal traffic management, platooning, optimal driving strategies and route planning. The environmental benefits of automated road vehicles (AV's) may be leveraged by sharing (SAV's) andelectrification (SAVE's), if the electricity is obtained throughlow-carbon sources. Road vehicle GHG emissions are expected to decrease, mainly due to replacement of (conventional)vehicles owned with a smaller number of automated (shared and electrified) vehicles.

On the other hand, other factors may lead to an increase in the GHG emissions:higher vehicle km's travelled (due to higher accessibility for younger people, seniors and people with special needs to mobility), higher average speeds (due to optimised traffic flow), and higher use of mobility in general

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(because lower costs per km) are pathways to higher levels of GHG emissions. Emissions may also increase because of the empty SAV's returning home or to parking places, searching for parking places or driving to pick up new passengers, and similarly, their empty tripsfor refueling and recharging may increase vehicle km's travelled and energy use.

Some of the other effects that may take place are:urban sprawl (because of easier commuting), urban densification (denser communities because of no/less garages and no/less parking lots needed), highway engineering (a new era with significant physical infrastructure modifications like narrower lanes), off-road applications (e.g. agricultural vehicles, mining vehicles or construction machines), and automated mobility on public or private land (e.g. automated shuttles, campus commuters).

This study presents a high-level analysis of the impacts of vehicle automation, sharing and electrification on energy use in road vehicles, with a focus on British Columbia (BC), Canada. The paper presents hypothetical scenarios for the transformation of the Province's mobility, based on road vehicles, over the years 2030 and 2040. The paper opens with a literature review, followed by analysis of various scenarios and discussion of insights into the SAVE's implications for BC.

Literature Survey

Energy use and GHG emissions:

Miller and Heard (2016) state that though individual GHG emissionofeach functional SAVcan be reduced(for passenger-km), an overall increase in GHG emissions originating from all transportation operations is not unlikely.Fagnant and Kockelman (2014) indicate that each SAV can replace 11 conventional vehicles, and adds up 10% more travel distance than comparable non-SAV trips, so an overall beneficial emission impact is to be expected.According to (Stephens et al. 2016), the effects of CAV's may lead to results with a broadband character. A 60% reduction or increase up to 300% in energy consumption is expectedfor the case of replacement of nearly all light duty passenger vehicles in the United States.Wadud et al. (2016)also positsresults in both directions for energy use in the US depending on how real-world adoption evolves;they finda decrease by a factor of 0.5 ofan increase by a factor of 2.0 in their study. Delucci et al. (2014) analyses battery electric, hybrid electric and fuel cell vehicles in terms of technology, infrastructure requirements, greenhouse-gas emissions, petroleum use, material use, lifetime cost, consumer acceptance and policy initiatives. The authors conclude that the new electric vehicle era will reduce GHG emissions in most of the cases studied. The electrification of transportation accelerates the integration of renewable energy sources onto the electrical grid and thus to the vehicles aiming zero GHG emissions.In this study, we focus on travel-based energy consumption and emissions as in (Wadud et al. 2016) since lifecycle impacts of vehicle automation and sharing are to be expected smaller in magnitude.

Vehicle km's travelled:

Numerous researchers have investigated the VMT (vehicle miles/km's travelled) per individual vehicle or in total. Vehicle automation is expected to increase VMT, especially in connection withunderserved populations, seniors, people with medical restrictions and younger people with no driver's license (Harper et al., 2016).

Driving strategy optimizationand platooning:

For widely adopted platooning, Wadud et al. (2016) estimated an energy intensity reduction between 3% and 25% for light duty vehicles. The authors calculated a reduction of 10-25% in energy intensity for freight trucks.Wadud et al. (2016) concluded that a wide application of eco-driving practices (implemented in automated vehicles on road networks) might deliver little system-wide benefit. Garcia-Castro et al. (2017) note that if smoother accelerations/decelerations and longer headways are used on high traffic demand areas, emissions rise, because of increased congestions and lower capacity. In terms of emissions, the effects of eco-driving are positive in low or medium demand areas with increasing number of eco-drivers.Stern et al. (2018) performed a field test with automated vehicles and concluded that even less than a 5% share of automated vehicles in a traffic flow can dampen and manage the traffic flow. This finding can help transport authorities to manage traffic in critical passages before most vehicles in traffic are automated.

Occupancy rates:
If the era of shared and automated vehicles can bring about the optimum occupancy rates in trips, there is a high potential for saving energy,depending on vehicle size and mass. Wadud et al. (2016)notes some hypothetical scenarios with optimized occupancy traffic for the U.S. Their assumptions quantify fuel consumption savings of up to 45% in an optimistic scenario, especially when supported with car sharing.
Market Adoption Scenarios:
Automated vehicles are accommodated in 33 states of the U.S. on public roads (Global Survey of Autonomous Vehicle Regulations,2018). There are different levels and types of activity in automated vehicle research, development and testing in the UK, Canada, Sweden, Germany, France, China, South Korea and Netherlands. Singapore and New Zealand have legislation that does not require vehicles to have drivers (Global Survey of Autonomous Vehicle Regulations, 2018).The conventional form of mobility based on human-driven and owned vehicles with internal combustion engines is evolving towards a concept that provides mobility as a service (Mobility as a Service - MaaS). The vehicles used within this service landscape will gradually have higher levels of automation and electrification.Walker (2019) states that global auto makers are ready for their first AV products on a timeline between 2017-2021. (Tesla in 2017; Toyota, Honda, Renault/Nissan, Hyundai and Daimler in 2020; Ford, Volvo, Fiat/Chrysler and BMW in 2021).(Look Ma, No Hands! 2012) proposes 75% of all heavy-duty vehicles in UK will be fully automated by2040.Greenblatt and Shaheen (2015) note that automated vehicles will be an emerging phenomenon in 2020, an accepted technology in 2030 and the dominant personal transportation medium by 2050.The adoption scheme of SAV's can be one of the most dominant factors in determining whether the GHG emissions related with land vehicle transportation in total will rise or fall (Miller and Heard, 2016).The BP Energy Outlook (2018) states that, in 2040, 3% of motor vehicles in traffic will be shared and human driven, 20% shared and automated, and 7% privately owned and automated.Expected early adapters for SAV's are fleets (e.g.,taxi fleets, bus fleets, delivery vehicle fleets) and (highway) heavy-duty-trucks with platoon automation.Autonomy of on-road vehicles can accelerate the adoption of shared mobility services since the need to go to central locations to pick up shared vehicles will diminish. If the vehicles can travel to the places where the demand is, this might boostthe popularity of on-demand services.

Current Road Vehicle Energy Use and GHG Emissions in British Columbia (BC)

Figure 1 provides an initial look into road transportation energy use in British Columbia, Canada, and illustrates the increasing trend in energy use for road transportation,caused mainly by freight transportation. Passenger transportation using road vehicles displays a slight decrease.Figure 1 is based on NRC data (Transportation Sector – British Columbia and Territories, (n.d.)).

Figure 2 depicts the energy use and GHG emissions of cars in BC,and is based on NRC data (Transportation Sector – British Columbia and Territories, n.d.). The source data showsan average energy use of 88 kWh per 100 km for carsin the period 1990-2016. The energy use of cars is predicted to be smaller than 80 kWh per 100km in the coming years. The average GHG emissions for cars in this period is 220 g/km and showa tendency to drop to 200 g/km in the coming years. The NRC data is evaluated for cars, buses (school buses, urban transit and inter-city buses) and trucks (passenger light trucks, freight light trucks, medium trucks and heavy trucks) within this study, and the summary is given in Table 1.

Vehicle electrification has good examples in the market, pertaining to cars and urban transit vehicles. School buses, passenger light trucks and freight light trucks will be present in the market soon. Vehicle sharing has started with cars. Most of the examples of automated vehicles are cars or heavy-duty trucks in platooning applications. Electric cars are very small in numbers and electric trucks do not exist as commercial products on BC roads apart from some small demo trials. As a result, electric vehicles are almost absent in BC transportation statistics until 2016. Statistical data on urban transit buses (which mainly arises from trolley buses in Vancouver area) is the only data available that could be used to discuss the share of electric energy use for road transportation. Since vehicle sharing and automation are new technologies and adoption rates are relatively small, no data exists for the past decades until 2016 in the relevant sources of BC Government or other institutions. Figure 3 shows the BC motor vehicle stock and car stock per 1000 inhabitants. The car density is nearly constant, while the motor vehicle density increases. The increase in BC's population is also embedded in Figure 3 which will play a role in the energy use scenarios of this study. Vehicle densities in 2030 and in 2040 are highly uncertain mainly because of the effects arising from vehicle sharing and automation.

Figure 1. BC Road Transportation Energy Use
(Transportation Sector – British Columbia and Territories, (n.d.))

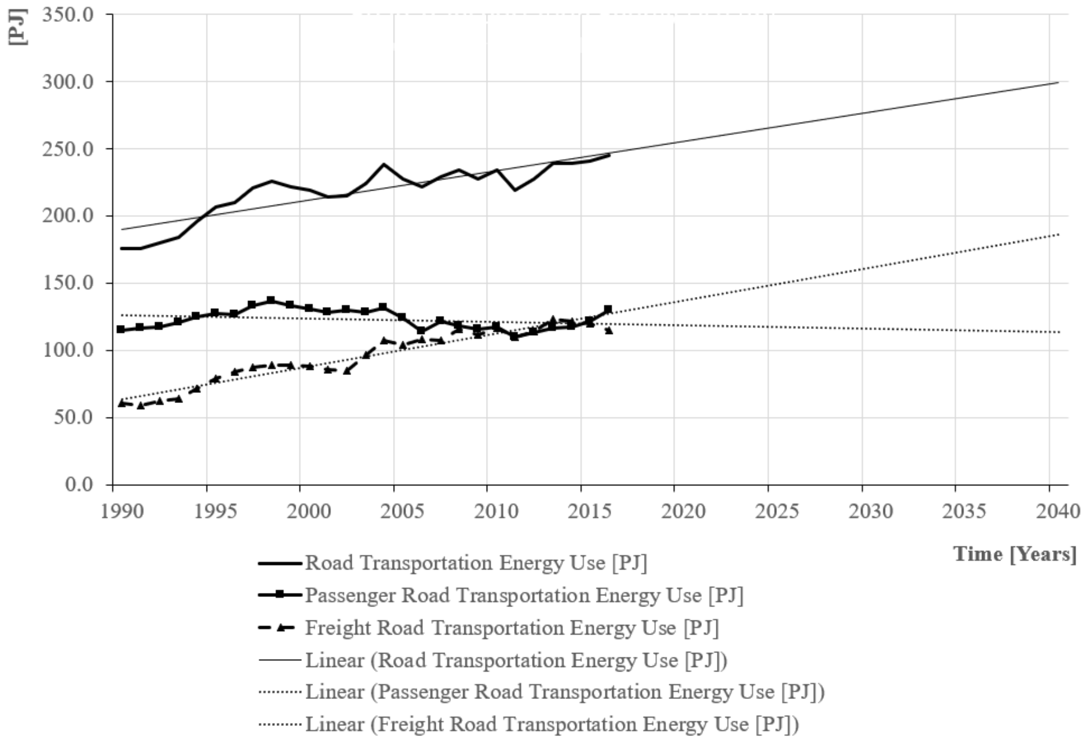

Figure 2.BC Cars: Distance Traveled, Energy Use & GHG Emissions (1990-2016)
(Transportation Sector – British Columbia and Territories, (n.d.))

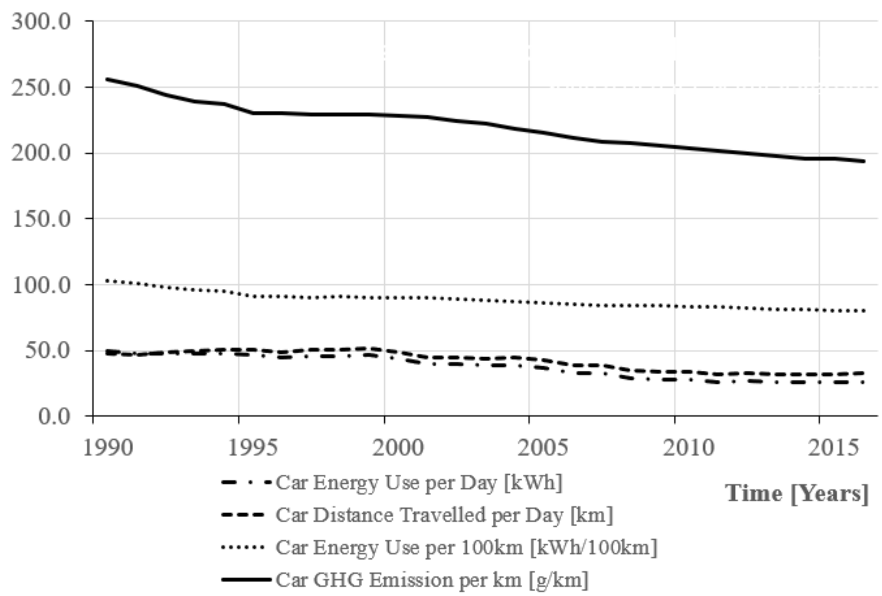

Table 1 BC Vehicles: Energy Use and GHG Emissions
(Transportation Sector – British Columbia and Territories, (n.d.))

BC Road Vehicles		Average 1990-2016	Tendency <
Cars	Energy use per 100 km	88 kWh	80 kWh
	GHG per km	220 g/km	200 g/km
School Buses	Energy use per 100 km	324 kWh	300 kWh
	GHG per km	818 g/km	800 g/km
Urban Transit	Energy use per 100 km	570 kWh	570 kWh
	GHG per km	1306 g/km	1300 g/km
Inter-city buses	Energy use per 100 km	391 kWh	390 kWh
	GHG per km	997 g/km	900 g/km
Passenger Light Trucks	Energy use per 100 km	118 kWh	110 kWh
	GHG per km	295 g/km	270 g/km
Freight Light Trucks	Energy use per 100 km	120 kWh	110 kWh
	GHG per km	296 g/km	270 g/km
Medium Trucks	Energy use per 100 km	251 kWh	220 kWh
	GHG per km	627 g/km	550 g/km
Heavy Trucks	Energy use per 100 km	413 kWh	400 kWh
	GHG per km	1058 g/km	1025 g/km

Figure 3.BC Motor Vehicle Stock and Car Stock per 1000 Inhabitants

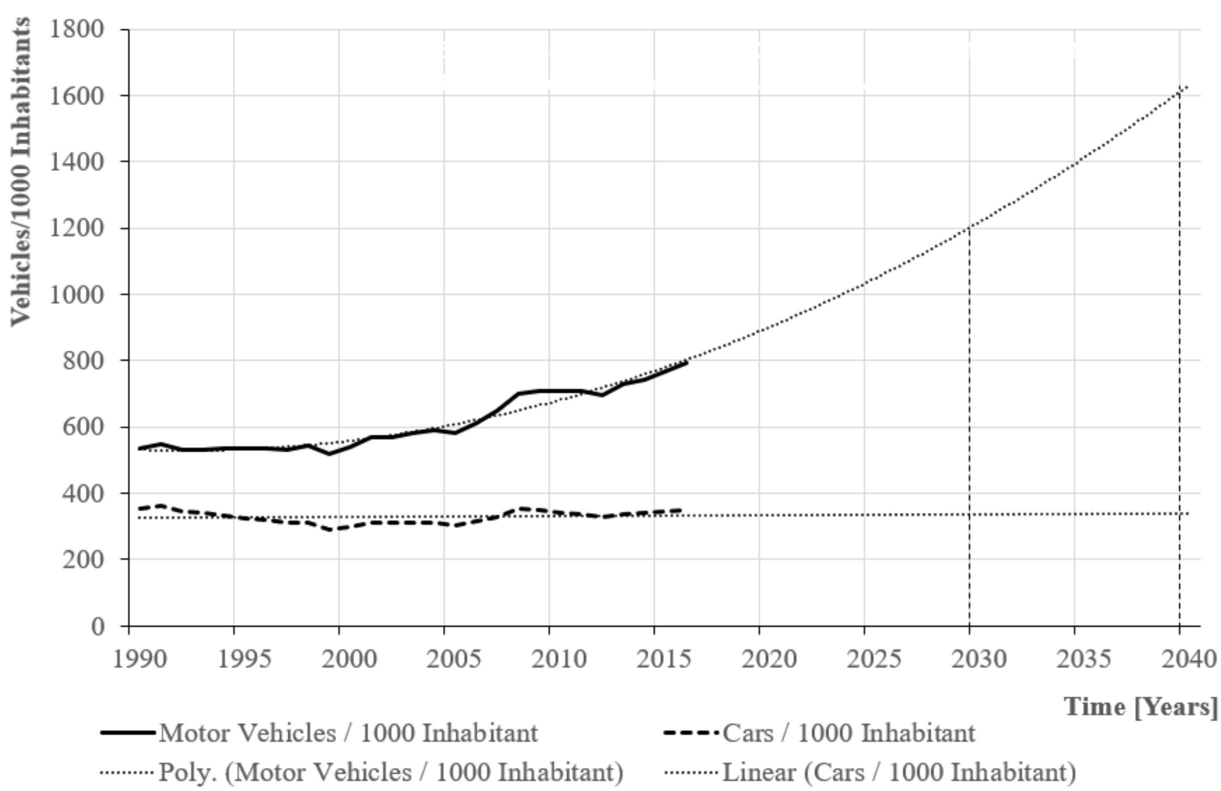

Table 2. BC Road transportation energy use scenario descriptions for the next two decades

Context	Effect	Literature / Source	Remarks	Technology	2030 Base Scenario Change in [%]	2030 Disruptive Scenario Change in [%]	2040 Base Scenario Change in [%]	2040 Disruptive Scenario Change in [%]
Less need for road vehicles	Decreased need for being on site	Levinson and Krizek 2017	Drones or other services do package delivery, virtual reality reduce the need for real site visits, etc.	VR, AR, Delivery services	-2	-5	-15	-25
Shared vehicles	Optimization: vehicle size and occupancy rates	Brown 2014, Wadud et al. 2016, Taiebat et al. 2018, Fox-Penner et al. 2018	Optimal selection of vehicle size and occupancy rate for the particular driving task	Sharing	-15	-20	-30	-40
Social impact	Mobility gain: Youth	Brown 2014, Harper et al. 2016, Wadud et al. 2016	Underserviced/Nonserviced population gets mobility	Automation	4	6	6	10
Social impact	Mobility gain: Seniors	Brown 2014, Harper et al. 2016, Wadud et al. 2016	Underserviced/Nonserviced population gets mobility	Automation	4	6	6	10
Social impact	Mobility gain: Handicapped people	Brown 2014, Harper et al. 2016, Wadud et al. 2016	Underserviced/Nonserviced population gets mobility	Automation	4	6	6	10
Social impact	Mobility gain: Low cost of vehicle km's	Brown 2014, Wadud et al. 2016	Everyone wants travel more	Automation, Sharing and Electrification	10	15	20	40
Urban design	Urban densification		More dense cities	Automation, Sharing	-4	-6	-7	-10
Urban design	Urban sprawl	Taiebat 2018, Driving Change 2018	More spreaded cities	Automation, Sharing	4	6	7	10
Vehicle Design	Optimization: motor size	Brown 2014, Wadud et al. 2016	No need to high accelerations, smoothed speed profiles	Automation	0	0	0	0
Vehicle Design	Optimization: vehicle weight	Brown 2014, Wadud et al. 2016, Taiebat et al. 2018	No collisions, passive safety measures reduced	Automation	0	0	0	0
Vehicle design	Extra drag	Gawron et al. 2018	Extra drag because of extra hardware extremities	Automation, Sharing, Electrification	0	0	0	0
Vehicle design	Extra weight	Gawron et al. 2018	Extra weight because of additional hardware	Automation, Sharing, Electrification	0	0	0	0
Vehicle design	Extra power consumption	Gawron et al. 2018	Extra power consumtion of additional hardware	Automation, Sharing, Electrification	0	0	0	0
Vehicle Design	Electrification	Brown 2014, Taiebat et al. 2018	Great CO2 reduction potential according to grid source (using renewables)	Electrification	-15	-20	-35	-50
Vehicle Fleets	Fleets of automated vehicles	Greenblatt J. B., Saxena S. (2015) *	Taxi fleets*, Bus fleets, delivery fleets, heavy duty truck fleets	Automation	-3	-5	-5	-8
Vehicle Operation	Platooning	Brown 2014, Wadud et al. 2016, Taiebat et al. 2018, Fox-Penner et al. 2018	Drag reduction	Automation	-3	-4	-5	-6
Vehicle Operation	Optimization: speed changes and stops	Brown 2014, Wadud et al. 2016, Fox-Peener et al. 2018	Less congestions and collisions, optimal traffic management and routing	Automation	-8	-10	-10	-12
Vehicle Operation	Optimization: driving route	Brown 2014		Automation	-4	-5	-5	-8
Vehicle Operation	Optimization: average travel speeds	Brown 2014, Wadud et al. 2016, Fox-Peener et al. 2018	Less congestions and collisions, optimal traffic management and routing	Automation	3	5	5	10
Vehicle Operation	Parking	Brown 2014	Energy use for parking	Automation, Sharing	-3	-4	-4	-5
Vehicle Operation	Fueling/Charging		Empty travels for fueling or charging	Automation, Sharing, Electrification	-1	-3	-3	-4
Vehicle Operation	Transport Mode Shifts	Taiebat et al. 2018	On-road long distance travels instead of rail or air	Automation, Sharing, Electrification	2	5	5	7
Vehicle Operation	Deadheading		Empty travels for various reasons	Automation, Sharing	3	5	4	2
Scenario	Cumulative impact of scenario				**-24.5%**	**-30.3%**	**-54.7%**	**-68.2%**
Population	BC Population growth	BC Government Statistics			13.5	13.5	24.5	24.5
Scenario & Population	Cumulative impact of scenario & population growth				**-14.3%**	**-20.8%**	**-43.6%**	**-60.4%**
Specific energy use	BC road transportation specific energy use: Energy use of passenger and freight transportation per inhabitant per year	Natural Resources Canada, BC Government			-2.2	-2.2	-2.1	-2.1
Scenario & Population & Specific Energy Use	Cumulative impact of scenario & population growth & specific energy use				**-16.2%**	**-22.6%**	**-44.7%**	**-61.2%**
Scenario & Population & Specific Energy Use & No Powertrain Electrification	Cumulative impact of scenario & population growth & specific energy use (No powertrain electrification)				**-1.4%**	**-3.3%**	**-15.0%**	**-22.4%**
BC Road Transportation Energy Use - Standard Trend		Natural Resources Canada			**9.5%**	**9.5%**	**18.2%**	**18.2%**

Scenarios

This study proposes two hypothetical scenarios for changesin road transportation in BC (Table 2). The first "base" scenario keeps its numeric predictions of factors affecting the energy use generallywithin the limits foundin literature data, whereas the second "disruptive" scenario, foresees a more aggressive scheme inspired by other more recent technology disruptions (e.g. digital photography, mobile phones, internet use). The main effectsof these scenarios are summarized in Table 2, with the sources used to develop the ranges of estimates for change quantities. It represents effects in various categories including vehicle design, vehicle operation, social impacts, urban design, vehicle fleets, vehicle sharing and other technology disruptions affecting the need of transportation. Wide adoption of shared, automated and electrified road vehicles (SAVE's) will doubtlessly change the energy use and GHG emissions of transportation. The literature shows both decreasing and increasing tendencies, frequently both within the same publication. The scenarios in our study all show decreasing tendencies for energy use and correspondingly GHG emissions, if vehicle automation and sharing is adopted in parallel to vehicle powertrain electrification using renewable energy sources.The mobility metrics or vehicle properties which are not expected to change until 2040 are shown in white cells in Table 2. These parameters are not expected to change much since conventional vehicles and SAVE's will share the same road network to a large extent. In this sense, vehicles have to be designed and operated compatible with active and passive safety standards of human-operated vehicles.

Results

Table 2 shows that the three major factors causing energy use changes are: size- and occupancy-optimized use of shared vehicles, powertrain electrification and the increase of vehicle km's travelled because of lower km costs. The base scenario shows a decrease of 24.5% and 54.7% for the energy use in the years 2030 and 2040 respectively. The disruptive scenario has a cumulative decreasing effect on energy use of 30.3% and 68.2% for the years 2030 and 2040 respectively. The cumulative scenario impacts need to be calibrated, taking two effects into consideration. The first effect is the expected population growth in BC. The second calibration considers the road transportation energy use per inhabitant per year in BC. After these corrections, the base scenario results are 16.2% and 44.7% decreases for 2030 and 2040 respectively. The disruptive scenario results are 22.6% and 61.2% decreases for 2030 and 2040, respectively. The same scenarios can also be calculated without the effect of vehicle electrification. Without electrification, the energy use decreases for the base scenario are reduced to 1.4% and 15%, and the energy use decreases for the disruptive scenario are reduced to 3.3% and 22.4% for 2030 and 2040 respectively. The Natural Resources Canada data on road transportation energy use (Table 2-last row) presents an increase for 2030 and 2040 (linearly extrapolated). This trend will probably change due to the new and disruptive technology adoptions in the next two decades. The road transportation energy use decrease proposed in this study is also in correlation with the data given in (Canada's Energy Future 2018).

Conclusions

In this study, road transportation energy use in British Columbia, Canada has been analysed for the years 1990-2016. Energy use and GHG emissions statistics for vehicle classes are summarized. The trends in transportation energy use and vehicle ownership are presented. Based on statistical data from Natural Resources Canada and BC Government, hypothetical scenarios describing changes in the mobility habits of the province are proposed. Aspects related to vehicle design, vehicle operation, urban design, vehicle sharing, and fleet operation are quantified within the limits of data found in the literature and some effects are intentionally set outside of those limits to gauge the effects of adoption of disruptive technologies: vehicle sharing, automation and electrification. All scenarios show a decrease in energy use for the years 2030 and 2040, which can encourage policy makers and stakeholders to incorporate these new technologies. A clear benefit can be observed if all technologies; vehicle automation, vehicle sharing, and vehicle electrification are adopted simultaneously. A clear benefit is to be expected, since BC's electric energy is generated using renewable sources, to a large extent.

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