# Vehicle Automation and Its Potential Impacts on Energy and Emissions

**Matthew Barth, Kanok Boriboonsomsin and Guoyuan Wu**

**Abstract** Interest in vehicle automation is at an all-time high, with many recent real-world demonstrations from a variety of companies and research groups. The key fundamental building blocks for automating vehicles have been in development for many years, making vehicle automation a near-term reality. Also in recent years, there have been significant efforts to make vehicles more energy efficient and less polluting, through the development of advanced powertrains and the development and promotion of alternative lower-carbon fuels, as well as traffic system operational improvements. With these two developing areas, one of the key questions is how will vehicle automation affect overall traffic energy efficiency and emissions. In this chapter, we briefly outline some of these potential impacts, examining issues such as vehicle design, vehicle and traffic operations, and even potential changes in activity patterns.

**Keywords** Vehicle automation • Energy • Environment • Platooning • Traffic smoothing • Traffic congestion

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## 1 Introduction

In the last few years, there has been a surge of interest in vehicle automation; there are now a number of workshops and conferences that are addressing a variety of important issues associated with vehicle automation that go beyond just the technical challenges (e.g., see [1, 2]). These issues include definitions, safety, mobility, environmental impacts, liability, privacy, security, reliability, insurance, cyber-security, human factors, human machine interfaces, certification, and licensing. As an example, one of the latest workshops has been the Transportation Research Board Workshop on Road Vehicle Automation in July 2013 which highlighted the state-of-the-art vehicle automation efforts by Google [3] and several automobile manufacturers, as well as addressing the different issues outlined above [1]. In addition to these conferences, there have also been a number of vehicle automation demonstrations taking place in a variety of environments. Even though these demonstrations have captured the general public's interest, it is important to realize that many automobiles today already have "partial automation" features such as anti-lock braking systems, electronic skid protection (i.e., positive traction control), adaptive cruise control, and lane keeping assistance, to name a few. As such, these automated vehicle efforts build on decades of vehicle advancements in safety, mobility, and driver conveniences.

In addition to vehicles becoming increasingly safe and convenient over the years, they have also become more fuel efficient and far less polluting. In the last decade, there has been a strong push to reduce greenhouse gas emissions from vehicles through a variety of means: (1) by introducing advanced powertrains (e.g., hybrid vehicles) and building vehicles with lighter (but stronger) materials; (2) by developing and introducing alternative lower-carbon fuels; (3) by implementing a variety of programs that aim to reduce overall vehicle miles traveled such as roadway pricing; and (4) by introducing better traffic operations, making traffic more efficient.

Given these two general areas of vehicle advances, it is important to consider the impact of vehicle automation on energy consumption and emissions (both greenhouse gases such as carbon dioxide, as well as pollutant emissions such as carbon monoxide, hydrocarbons, oxides of nitrogen, and particulate matter). There are several dimensions that must be considered, including vehicle design, vehicle and traffic operations, and even potential changes in activity patterns which may lead to additional travel. In this chapter, we primarily address vehicle and traffic operation issues associated with automation and the impacts it may have on energy and emissions.

## 2 Energy and Emissions Impacts of Traffic

In order to better understand transportation impacts on energy/emissions in general, it is useful to examine traffic as a function of average travel speed. In [4], the authors have developed a methodology that takes individual snippets of vehicle operation (i.e., vehicle velocity trajectories), applies them to a microscopic energy/emissions model, then uses the resulting values to characterize energy/emission effects as a

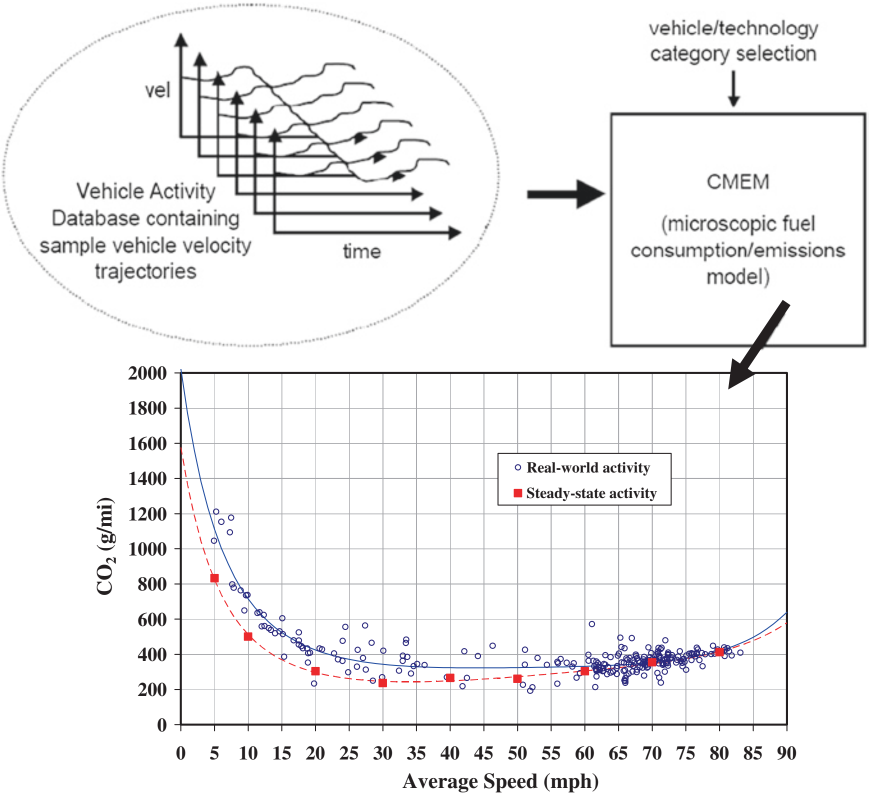


**Fig. 1** Methodology of generating an energy/emissions curve as a function of average traffic speed (see [4])

function of average traffic speed. This general methodology is illustrated in Fig. 1. With enough snippets representing a wide variety of conditions and trips, a general curve emerges as shown in Fig. 1, relating energy or emissions (on a grams/mile basis) to average speed. This figure represents an average light duty vehicle type where the blue line represents carbon dioxide emissions as a function of average traffic speed. Also shown in this figure is a dashed red line, which represents the lowest energy or emissions that a vehicle can possibly achieve at any particular speed, made up of individual trips that have (unrealistic) constant speeds with no accelerations and decelerations. In addition to carbon dioxide shown in Fig. 1, other pollutant emissions are shown for this example average light duty vehicle type in Fig. 2.

These figures generally show that energy and emissions, normalized by distance traveled, are high at very low average speeds simply because the vehicles are on the road longer and therefore have higher energy and emissions for that particular type of driving. The energy and emissions then tend to flatten out at mid-range speeds (e.g., 35–55 mph), before increasing again at higher speeds (55 mph and above). This increase at higher speeds is due to increased aerodynamic drag forces; the vehicle's engine must work harder to maintain those higher speeds.

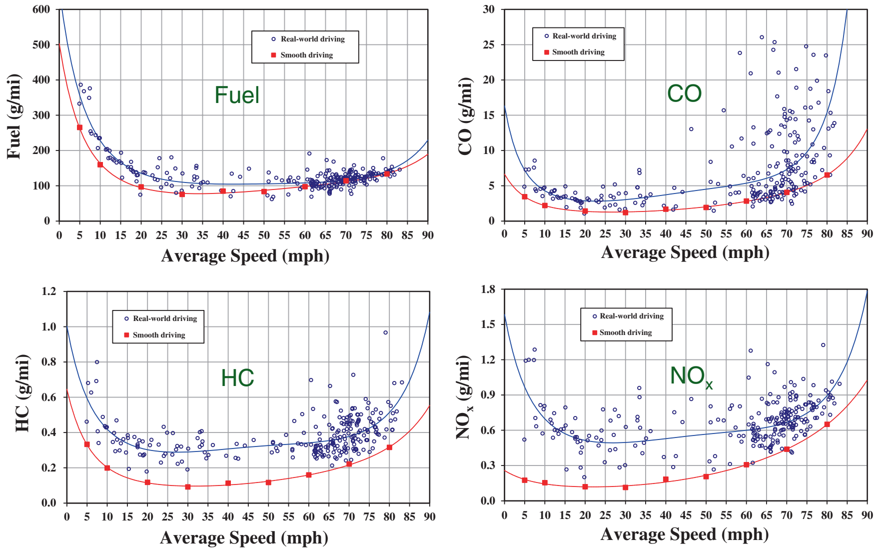


**Fig. 2** Energy and emissions as a function of average traffic speed (see [4])

## 3 Vehicle Automation Impacts

Given these generalized energy/emission versus speed figures, it is now possible to identify the general areas where vehicle automation can potentially impact energy and emissions. Three general areas emerge, as shown in Fig. 3.

(1) The first area deals with reducing roadway congestion in general, which is an important mobility issue. Vehicle automation can potentially reduce roadway congestion in a number of ways, as described further in Sect. 3.1. When congestion is reduced, average traffic speeds increase, and average energy and emissions go down.
(2) Another way vehicle automation can reduce energy and emissions is by introducing platooning as part of the automation. Platooning effects are described in greater detail in Sect. 3.2.
(3) The third general area where vehicle automation can impact energy and emissions is through traffic smoothing effects. Vehicle automation has the potential to reduce the sharp stop-and-go characteristics of today's traffic, as outlined in Sect. 3.3.

### *3.1 Traffic Congestion Reduction*

In the case of human manual driving, we can characterize driving behavior with car-following models and lane change logic. As part of this behavior we have to deal with reaction delays and different sensitivities on how closely drivers follow

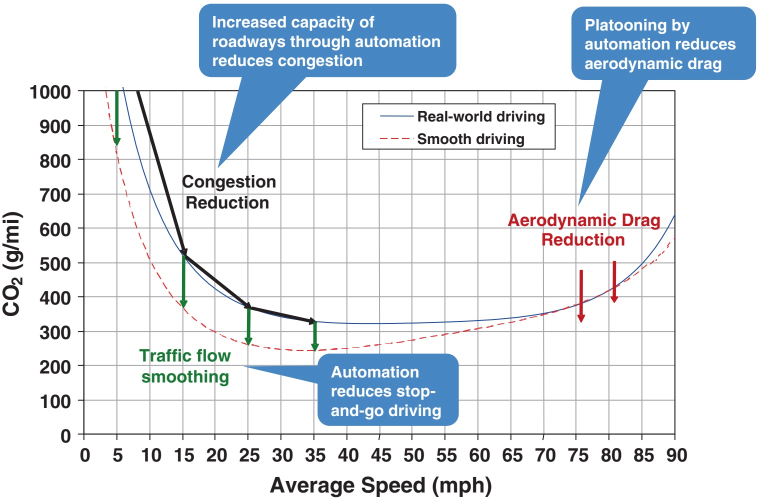


**Fig. 3** General impacts of vehicle automation on energy and emissions, using data from Fig. 1

other vehicles. Under heavy traffic demand, the traffic flow often breaks down into a congested regime that limits the overall capacity of the roadway. Also with human driving behavior, we often get sharp stop-and-go effects in the traffic flow which is highly detrimental for fuel consumption and emissions.

In the case of vehicle automation, it is possible that vehicles can safely follow each other more closely with faster reaction times while in traffic, thereby increasing the net capacity of the roadway (in terms of vehicles/hour/lane). However, it is very important to distinguish between *autonomous* vehicles and *automated* vehicles in the analysis. These two terms are often used interchangeably, however there is a significant difference when considering how vehicles interact in traffic and with associated congestion. An autonomous vehicle typically relies almost entirely on its on-board sensors to make driving decisions, just as humans do. This is in contrast to automated vehicles, which in addition to on-board sensors, they can also take advantage of vehicle-to-vehicle communications, as well as infrastructure-to-vehicle communications. In the case of an autonomous vehicle, processing sensor information and making decisions solely on that information can sometimes take just as long as human drivers. Therefore, for autonomous vehicles, it is unlikely that there will be significant capacity improvements on the roadway due to vehicles not being able to follow each other very closely. For automated vehicles that can also communicate, much smaller gaps between vehicles are possible since communication can occur at a much higher rate. With these smaller gaps, there is the possibility for a net capacity increase.

In the case of automated vehicles with this increased capacity, roadway congestion can then be reduced, as long as the travel demand does not increase. This is illustrated in Fig. 3 where traffic moving at slower speeds would be able to now move at higher speeds due to less congestion, reducing energy consumption and emissions that are on the high left side of the energy/emission versus speed curve.

In addition to these capacity effects, there are many that have stated that with the advanced safety systems on automated vehicles, there will be fewer roadway accidents compared to human drivers. However, it is still unclear what the traffic accident rate will be with automated vehicles. On a mean-time-between-failure (MTBF) basis, today's traffic accidents are rather infrequent when counting up the total amount of vehicle-hours-traveled (VHT) or vehicle-miles-traveled (VMT). It will be a significant challenge for automated vehicles to reach that same level of safety. In any case, it is well known that traffic accidents cause significant delays and roadway congestion when they do occur. Any reduction in traffic incidents will result in less congestion, and therefore lower energy and emissions.

### *3.2 Vehicle Platooning*

Vehicle platooning is generally defined as two or more vehicles following each other close enough to where there is reduction in the aerodynamic drag forces on the vehicles. Race car drivers are well aware of these drafting effects and they use them to their racing advantage. Over the last two decades, there have been a number of experiments that have been carried out to show that vehicle platooning can reduce energy consumption and emissions (see, e.g., [5–7]). Many of these experiments have focused on trucks, since they typically have such high aerodynamic loads. As an example, Fig. 4 illustrates the energy reductions due to truck platooning, based on both wind tunnel testing and actual field study experiments. This figure shows the increased fuel savings as the separation between the vehicles decreases. It is important to note that not only is there a benefit for the following vehicles, the leading vehicles also get an aerodynamic benefit. In general, operating at separations of around 4 m, 10–15 % energy savings can be achieved [5].

Vehicle platooning can be accomplished safely by introducing sensing, control, and communication systems in vehicles. Because the control cycle occurs at a much higher rate compared to human drivers, it is possible to adjust the vehicle's speed and acceleration so that the vehicles can safely follow each other at close spacings.

Although platooning has been demonstrated in a variety of experiments, there are still a significant amount of research that needs to take place before it can become commonplace, including the design of safe platoon maneuvers (e.g., getting in and out of platoons).

### *3.3 Traffic Smoothing*

The third element where vehicle automation may have a significant impact on energy and emissions is due to smoothing traffic flow. In today's traffic, we often experience stop-and-go effects where vehicles speed up and slow down due to fluctuations in the traffic stream. As described in Sect. 3.1, the fluctuations

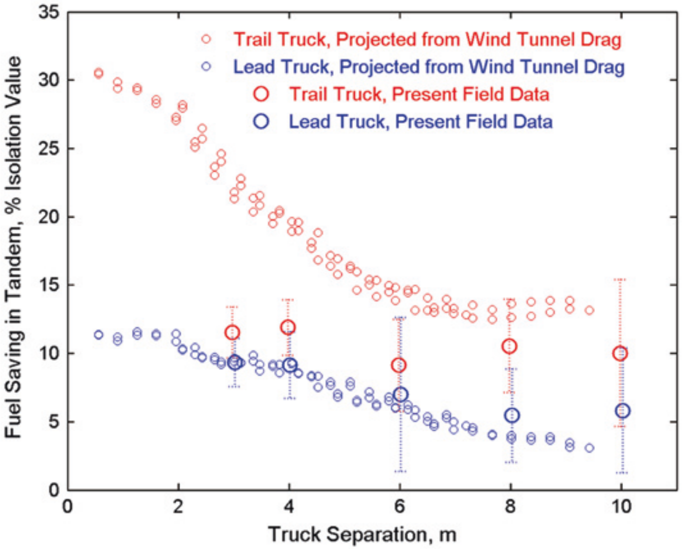


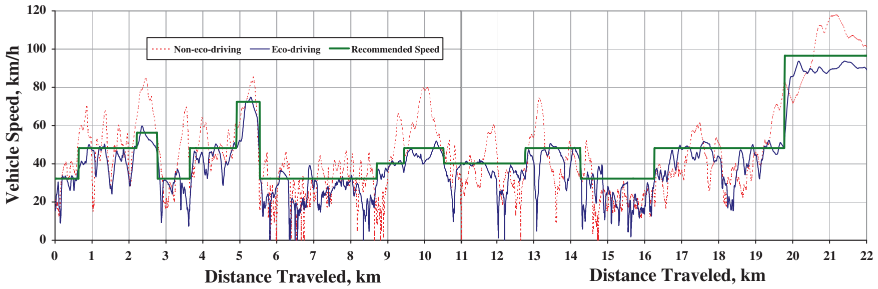
**Fig. 4** Fuel Savings from Truck Platooning, as a function of vehicle separation, from [5]. In this figure fuel savings are shown for both wind tunnel tests (*smaller circles*) and real-world platooning experiments (*larger circles*). The *red data points* correspond to a following vehicle while the *blue data points* correspond to the lead vehicle

are often due to shockwaves in the traffic flow that are caused in many cases by human driving behavior. There are several system-level automation techniques that can be applied to smooth the traffic flow. In Fig. 3, traffic smoothing techniques would essentially lower the blue energy/emission versus speed curve to come closer to the theoretical minimum depicted by the red dashed line, representing traffic moving at constant speeds.

There are many examples of automation that can potentially smooth traffic. These traffic smoothing techniques often use similar approaches, but they often go by different names, such as speed harmonization, variable speed limits (see, e.g., [8]), intelligent speed adaptation (see, e.g., [9]), traffic jam assist, highway piloting, and connected eco-driving (see, e.g., [10]).

It is important to note that the concepts of speed harmonization and intelligent speed adaptation target primarily safety and mobility issues; however, many of the papers cite an energy and emissions benefit as well. In contrast, the concept of connected eco-driving is primarily targeted at environmental benefits, even though the general approach is similar to the others.

As an example of a connected eco-driving application, Fig. 5 (from [10]) illustrates the general concept. If a vehicle receives automated speed recommendations as it travels down the road, it can help eliminate the stop-and-go effects we experience today. Figure 5 depicts a real-world experiment on a congested highway in Southern California, where one vehicle (depicted by the blue speed versus distance plot) gets speed advice based on forward-looking local traffic conditions. In



| Energy/Emissions | Non Eco-Driving | Eco-Driving | Difference |
|---|---|---|---|
| **Fuel (g)** | 1766 | 1534 | -13% |
| **CO2 (g)** | 5439 | 4781 | -12% |
| **CO (g)** | 97.01 | 50.47 | -48% |
| **HC (g)** | 3.20 | 1.90 | -41% |
| **NOx (g)** | 6.28 | 3.97 | -37% |
| **Travel time (min)** | 38.9 | 41.2 | +6% |

**Fig. 5** Connected eco-driving experiments showing traffic smoothing principles of automated driving (from [10])

contrast, a different vehicle (depicted by the red dashed line) doesn't get any speed advice and simply follows the traffic flow.

An algorithm is used to generate the dynamic speed advice, based on real-time inputs of traffic conditions on the roadway which is illustrated in Fig. 5 by the solid green line. The blue-line vehicle received this speed advice and followed it as closely as possible, naturally slowing down when necessary due to traffic. In this experiment, both the blue and red vehicles started at the same place and time, traveling for approximately 22 km through congestion. Both vehicles arrived at their destination approximately at the same time, however, the blue vehicle had significantly lower energy consumption and emissions, primarily by not having sharp accelerations then quickly having to decelerate once it hit a new pocket of congestion.

## 4 Other Automation Effects

In the analysis provided in Sect. 3, there are potentially significant energy and emissions savings that can be achieved, especially when all of these techniques can be implemented in parallel. If the different energy/emissions saving applications are truly independent, then the benefits cited can be additive. However, further research is needed to see if the different applications will be independent and if the savings can be additive.

Another area that can be considered part of the overall "automation" package is in the area of traveler information systems. A primary example of this is better route guidance that avoids areas of congestion and large changes in road grade. These so-called "eco-routing" applications have been in development for several years (see, e.g., [11]). A number of research efforts have shown that eco-routing can save as much as 20% energy and emissions, depending on the level of congestion in the roadway network. Some eco-routing algorithms are now being incorporated into on-board navigation systems. Another example of a traveler information system automation-related applications is smart-parking, where energy and emission savings are possible by reducing the amount of driving associated with searching for parking places in congested areas.

It is also important to note that vehicle automation is highly amenable to electric-drive vehicles. Electric-drive vehicles themselves have a large energy and emissions benefit; however greater synergies with automation are possible in terms of how automation can assist with providing electric energy to the vehicles (e.g., see [12]). Furthermore, the on-board energy management strategies of electric-drive vehicles (e.g., plug-in hybrid electric vehicles) can be specifically designed to take advantage of different automation regimes, including freeway driving, driving through automated arterial roadway infrastructure, and routing to known destinations [13]. It is highly likely that vehicle electrification and vehicle automation will go hand-in-hand in future developments.

Thus far, the majority of the discussion on energy and environmental impacts of vehicle automation has been citing potential benefits. However, there could potentially be a significant dis-benefit in terms of how travel demand could change, based on the introduction of vehicle automation. One of the key issues focuses on existing users of vehicles; if trips now become more convenient, reliable, and timely due to automation, will current users start making more trips and drive more? As such, it is unclear to what degree this “induced demand” or “rebound effect” will come about due to vehicle automation. Thus, further research is certainly warranted. Furthermore, it is also important to consider additional vehicle demand from *new* users that were not able to use vehicles until they become automated. Example users include youth, elderly, and disabled people. It may be necessary to couple the deployment of vehicle automation closely with more aggressive travel demand management schemes such that overall travel demand is kept in check.

## 5 Summary and Future Work

By using a generalized energy/emission versus speed curve for typical traffic, this chapter discusses the potential benefits of vehicle automation on reducing energy consumption and emissions, primarily from a vehicle and traffic operations point-of-view. Three general concepts were outlined, including the benefits of reducing congestion, taking advantage of vehicle platooning, and smoothing traffic flow. There are many specific examples of traffic congestion reduction mechanisms and traffic flow smoothing techniques through intelligent transportation system and automation deployment.

However, it is important to point out that vehicle automation also has the potential to fundamentally transform travel behavior in regards to trip profile, travel mode choices, vehicle ownership, activity location; all of these could lead to significant impacts on land use, energy consumption, and emissions. It is clear that more research is needed in this area, examining behavioral modifications of private, public, commercial and freight transportation resulting from automation.

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