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16. Abstract

Fuel consumption rates were studied from a naturalistic driving data set employing a fleet of identical passenger vehicles with gasoline engines and automatic transmissions. One hundred and seventeen drivers traveled a total of over 342,000 kilometers (213,000 miles), unsupervised, using one of the experiment's instrumented test vehicles as their own. Continuous monitoring of hundreds of data signals, including fuel flow rate, provides a unique data set of driving behavior with a common vehicle. The results are presented for both the overall fuel consumption as well as fuel consumption for speed-keeping and accelerating-from-rest events.

A substantial variation in the overall fuel consumption rate was observed. The differences between the mean consumption rate and the fuel consumption rates for the 10th and 90th percentile drivers were 13 and 16 percent, respectively, of the mean value. The corresponding differences between the 10th and 90th percentiles and the mean for both speed-keeping events and accelerating-from-rest events were up to 10 percent.

While some of the obtained variation in fuel economy is likely due to uncontrolled or unmeasured factors, such as passenger and fuel weight, and wind, the data imply that the behavior of real-world drivers adds significant variation to fuel consumption rates. The present findings suggest the possibility of substantial potential gains in real-world efficiencies through modification of driver behavior itself (e.g., through training), or for electronic modulation technology between the driver's foot and the throttle to modify a relatively wasteful driver into a more efficient one.

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Fuel consumption, individual variations, naturalistic driving

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The data used in this study are from the Integrated Vehicle-Based Safety System Field Operational Test, a project conducted by UMTRI under a cooperative agreement with the U.S. Department of Transportation. Jim Sayer of UMTRI was the project director. UMTRI's partners included Honda R&D Americas, Inc., who made possible the collection of data that enabled this analysis.

Contents

Introduction

This study seeks to quantify and characterize the variation in fuel consumption across automobile drivers in a naturalistic driving experiment. The study addresses use of passenger vehicles by the general public, and is designed to estimate the magnitude of variation that may be attributable to individual drivers, including overall fuel consumption rates and those for two key driving scenarios.

Reducing fuel consumption has become a critical issue in American society because it is related to goals of reducing dependency on foreign oil sources, reducing greenhouse gas emissions, and increasing economic vitality. Many approaches are being pursued to improve the efficiency of passenger vehicles. Vehicle designers are producing lighter and more aerodynamic vehicles, more efficient gasoline engines, new diesel technology, more efficient transmissions, tires with reduced rolling resistance, and hybrid-electric and all-electric powertrains. Vehicle designers, aftermarket providers, and even Internet sites are promoting eco-routing and eco-driving assistants to drivers. Among the technologies or services available are navigation devices to select fuel-efficient routes (manufacturer- or aftermarket-installed), real-time feedback related to instantaneous fuel usage, post-trip estimates of fuel use relative to peers, and so on.

Many factors influence actual fuel consumption, including the vehicle design; roadway factors such as grade and pavement; environmental factors including wind, air pressure, and temperature; traffic factors that influence the speed and variability of speed; and the individual driver's behavior. This study focuses on the individual driver factors. Previous studies of this topic have included studies in which a small number of drivers (typically 20 or less) were asked to drive along fixed routes, using either passenger vehicles (Evans et al., 1979, Lennar, 1995) or heavy vehicles (Ishiguro, 1997). In these and other studies, it has been shown that speed and speed variability—typically due to traffic and traffic control devices—have a significantly greater effect on fuel consumption than have the individual differences between drivers. Another study focused on the impact of an eco-driving aid and used drivers in their own vehicles (Boriboonsomsin, 2009). In this latter study, the differences among the diverse vehicle models prevent insight into quantitative measures of individual driver differences.

In this study, use is made of a new data set with a large number of drivers traveling in an unconstrained method for several weeks each. This data set is far greater in scope than any that were found in the literature. Thus, the differences between drivers can be extracted with more confidence. This data set consists of 117 drivers, each driving one of 16 identical instrumented vehicles in a naturalistic setting–that is, using the vehicle as their own, without supervision or instruction. Most of the drivers (103 of 117) drove the vehicles for 36 to 42 days. Seven drivers drove for longer periods–up to 49 days in one case. Seven drivers had a vehicle for less time, with two of those drivers having only 11 and 20 days, respectively, with the vehicle. During the drivers' travel, continuous data collection was done with an onboard system, capturing fuel use, speed, location, video, and hundreds of other variables. The data set originates from an experiment conducted to study the safety impact and driver acceptance of an integrated set of crash warning devices. The project, *Integrated Vehicle-Based Safety System (IVBSS) Field Operational Test*, generated an archive of 342,941 kilometers (km) (or 213,139 miles (mi)) of data, with 33,788 liters (L) (or 8,926 gallons (gal)) of fuel consumed (Sayer et al., 2010). The average distance traveled over the 40-day period was 3,175 km (1,973 mi), with drivers traveling as little as 911 km (566 mi) and as much as 8,901 km (5,532 mi). The vehicles were model year 2006 or 2007 Honda Accord SE (V6) with gasoline engines and automatic transmissions, purchased from a dealer. Cosmetic changes involving trim and other details were the only differences between the 2006 and 2007 model years. The fuel flow rate data was collected from the manufacturer's onboard system that reports to a resolution of 0.2 cc at a frequency of 10 Hz. The drivers included residents of southeast Michigan, a region that includes metropolitan Detroit, suburban areas, and rural areas. The large majority of driving was done in this region, an area of approximately 6,400 square miles of rather flat terrain. Less than 10% of travel was outside this region and included individuals traveling to other areas within Michigan and 12 other states.

The drivers were initially contacted using records provided by the Michigan Secretary of State, the licensing agency. Because this data set uses virtually identical vehicles, the effects of individual drivers are easy to isolate. Several reports describe the recruitment and driver-management procedures, including Sayer et al. (2008). The presence of the crash-warning devices is presumed to have little impact on drivers' use of the vehicles, including their speed and acceleration behaviors. The tested devices issued audio and haptic warnings to drivers and did not include active control of braking or steering.

Overall fuel consumption rates of drivers

The overall average fuel consumption of each driver was computed by dividing the driver's total fuel usage by his or her distance traveled. Figure 1 shows a histogram of the average fuel consumption rates of the drivers in this data set. The mean of the individual drivers' fuel consumption values is 10.1 liters (L) per 100 km (or 4.29 gal per 100 mi). (This is equivalent to 9.90 km/L or 23.6 mi/gal.) The percent difference between the mean and the fuel consumption values for the 10th and 90th percentile drivers are 13 and 16 percent, respectively, of the mean value. Thus, the variation in consumption is substantial.

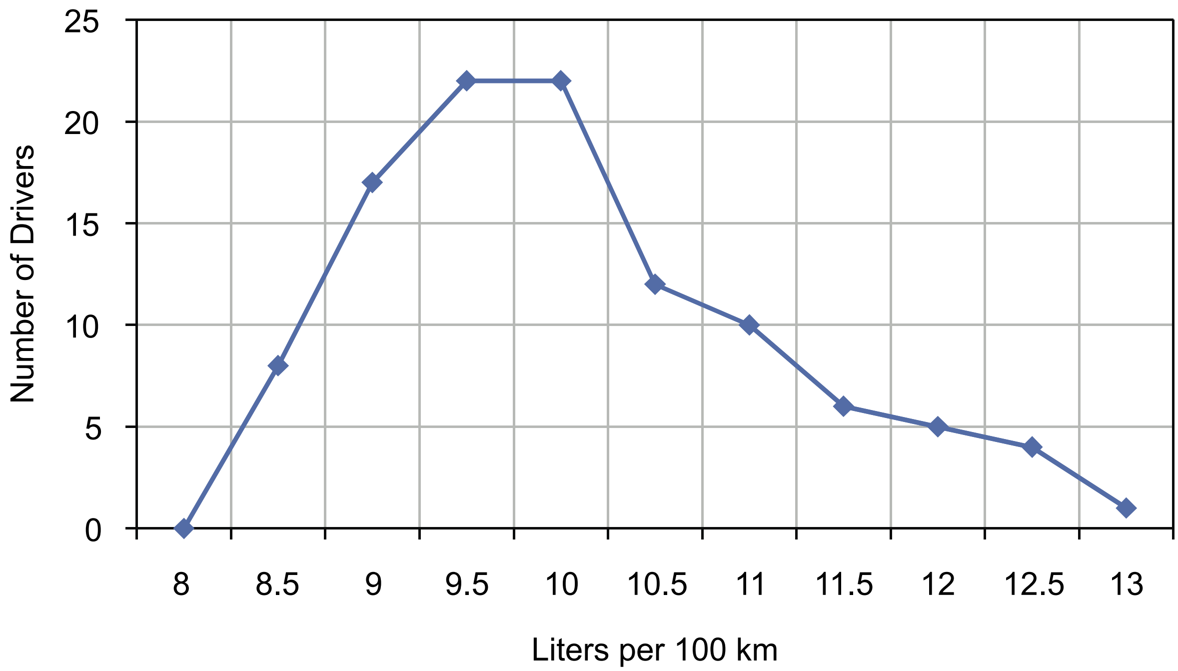

Figure 1. Average fuel consumption rates by individual drivers.

The variation in overall fuel consumption rates can be attributed to differences in routes, travel times, and driver choices about the speed and pedal behaviors along those routes. Route choices are important because the vehicle efficiency is related to speed when driving at constant speed, as will be shown later. Time spent idling is also a factor. Further variation is likely attributable to relatively small differences in the weight of the payload, i.e., the driver, passengers, cargo, and fuel in the tank. The differences in payload mass are not likely to be more than 70 kg from the average, which is less than 4% of the average mass, thereby contributing no more than a few percent of the overall fuel-consumption variation. Other smaller, random variations affecting efficiency include wind and snow cover. The vehicle and tires themselves were checked between drivers, with tire pressure and wear monitored and tires replaced in some instances.

Fuel consumption as a function of speed and acceleration

Fuel consumption rates vary considerably with speed, as is well known. For the IVBSS test, the dependence of fuel consumption rate on speed is illustrated in Figure 2, along with the travel exposures at different speeds. This figure was generated by considering the time, fuel use, and travel that was observed in the field test within 1 kph bins. Figure 2 shows that the traces of travel time and the fuel volume consumed share a common shape when plotted against travel speed, with peaks near zero speed (idling), 65 kph (travel on surface streets), and twin peaks between 110 and 120 kph (highway speeds). The distance trace mirrors the travel time trace (except, of course, there is very little travel distance at speeds near zero), and the distance trace is directly proportional to speed.

The fuel consumption rate, in liters per 100 km, is also shown using a secondary vertical axis. This curve shows the classic inefficiency of conventional powertrains near zero speed, with increasing efficiency as speed increases, until the consumption rate is 7.44 liters per 100 km at 98 kph, as indicated by the arrow on the figure. (This point equates to 3.18 gal per 100 mi at 61 mph.) As speed increases further, the system becomes less efficient, with rates climbing to about 10 liters per 100 km near 145 kph. The most travel in this field test occurred at 119 kph (or 74 mph).

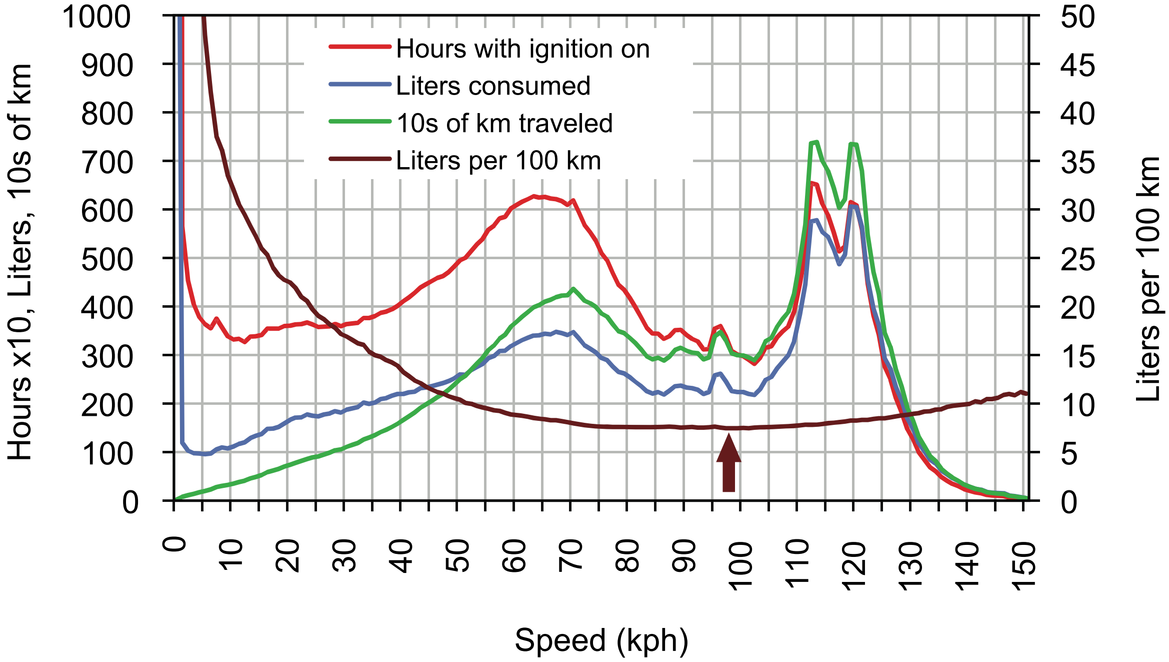

Figure 2. Travel and fuel consumption as a function of speed.

To find the driving modes that consume the majority of fuel, consider Table 1, which shows the percentage of all fuel consumed within 24 bins. These bins each correspond to a range of speeds and a range of accelerations. The speed bins range from a near-zero bin (less than 2.5 kph) to a bin for speeds of over 120 kph. The acceleration bins correspond to significant acceleration (more than 1.05 m/sec^2); notable acceleration (between 0.55 and 1.05 m/sec^2), approximately constant speed driving (between -0.55 and 0.55 m/sec^2), and notable decelerations (less than -0.55 m/sec^2). Fuel use in reverse gear accounted for less than 0.5% of all fuel consumed, and is not shown in this table.

Table 1
Liters of fuel consumed within speed-acceleration bins.

Mode	Accelerations (m/sec2)	Speed bins (kph)						All speeds
		<2.5	2.5 to 3.0	31 to 60	61 to 90	90 to 120	over 120	
Significant acceleration	more than 1.05	0.1%	4.6%	5.2%	1.0%	0.2%	0.1%	11%
Notable acceleration	0.55 to 1.05	0.1%	1.6%	4.0%	2.3%	0.8%	0.2%	9%
Speed almost constant	-0.55 to 0.55	5.7%	3.3%	10.1%	20.0%	27.9%	10.7%	78%
Notable deceleration	less than -0.55	0.2%	1.3%	0.5%	0.1%	0.0%	0.0%	2%
	All modes	*6%*	*11%*	*20%*	*23%*	*29%*	*11%*	*100%*

The following observations are made from Table 1 regarding fuel use in naturalistic driving:

- Only 6% of fuel is consumed at very low speeds. (Half of fuel represented in this number is while the vehicle is in "Park" gear, and the other half in "Drive" gear, which may in turn be dominated by time stopped at traffic signals, stop signs, congested roadways, and so on.)
- Twenty percent of fuel is consumed during acceleration events. The data show that only 6% of travel distance is accumulated during these acceleration events, so that acceleration events represent particularly high rates of fuel consumption, as expected. Most of that fuel is consumed at lower and moderate speeds; acceleration events above 90 kph account for only 1.3% of all fuel consumed in the test.
- Seventy-eight percent of fuel is consumed during times at which the speed is approximately constant. Travel during this type of driving accounts for 88% of all travel distance.
- Very little fuel (2%) is consumed during braking operations or non-braking situations in which the acceleration is less than -0.55 m/sec2.

Fuel consumption variation among drivers when acceleration is near zero

To gain insight into the role of individual driving styles in the variation of fuel consumption, two modes of driving are studied further:

- Constant speed travel
- Accelerations from rest to a constant speed

These modes are selected because they represent the dominant activities that consume fuel. Travel with small accelerations accounts for 78% of all fuel used, and acceleration events consume 20% of all fuel (but account for only 6% of all distance).

To study the variation among drivers during constant speed travel, two sets of speed-keeping events are isolated from the field test data. The first set is centered on 98 kph (the most fuel-efficient speed, as stated earlier), and the second set is centered on 119 kph (the most common travel speed). Both sets include periods of steady-state speed-keeping in which the average speed is close to those two speeds (plus or minus 2 kph). Average fuel consumption rates for those events are computed for individual drivers, in order to examine the variation of fuel use across drivers. Each event must last for at least 20 seconds, and only drivers with at least 10 events are considered. A histogram of the individuals' average rates is shown in Figure 1. The two histograms represent over 16,000 events.

Table 1 shows statistics of the individuals' fuel consumption for the steady-state speed-keeping process. As expected, the higher speed of 119 kph results in a higher fuel consumption rate than that observed at 98 kph. At both speeds, there is significant variation among individual drivers, with the 10^{th} and 90^{th} percentile drivers being about 10% lower and higher, respectively, than the mean value for the events at that travel speed.

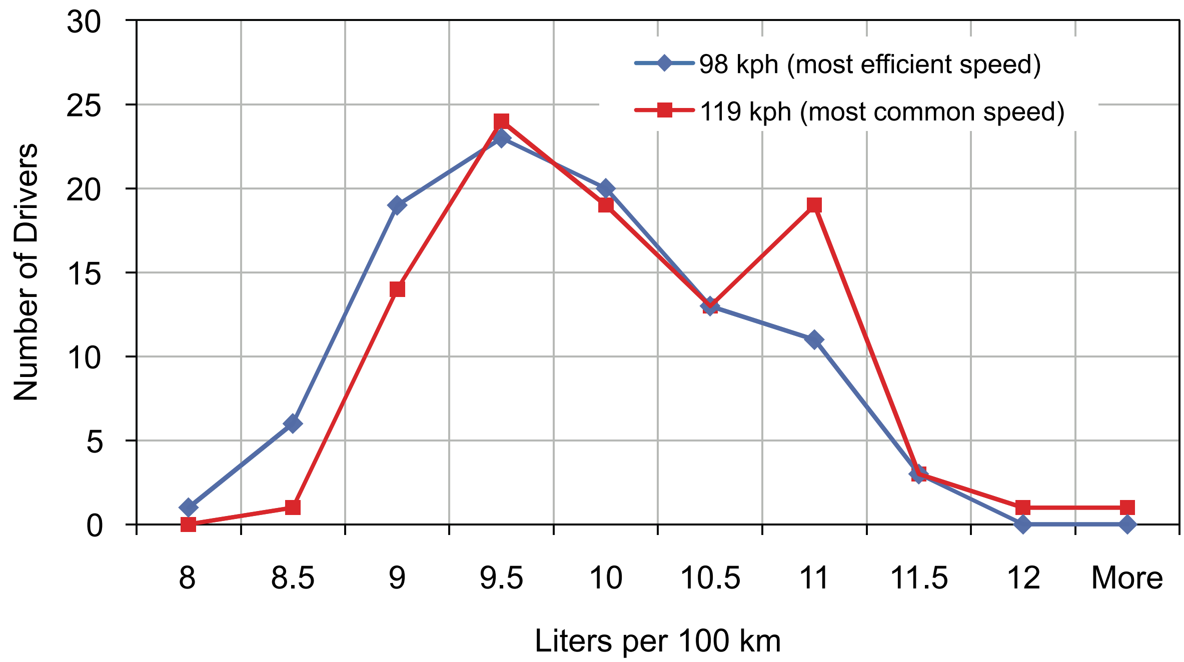

Figure 3. Individual drivers' mean fuel consumption rates while driving in speed-keeping mode at 98 and 119 kph.

Table 2
Individuals' mean fuel consumption rates for speed-keeping events (liters / 100 km).

Travel speed	Number of events	Mean of individuals' means	Standard deviation	10th percentile value (and difference from mean)	90th percentile value (and difference from mean)
98 kph	96 drivers 5602 events 29.2 hours	9.52	0.78 (8.2% of mean)	8.58 (-9.9%)	10.65 (11.8%)
119 kph	95 drivers 11016 events 47.8 hours	9.82	0.79 (8.1% of mean)	8.82 (-10.2%)	10.75 (9.5%)

Fuel consumption in accelerating-from-rest events

Earlier, Table 1 showed that acceleration events associated with at least 0.55 m/sec^2 account for 20% of the fuel consumed in drivers' travel. To understand the variation across drivers in fuel usage for acceleration events, the events were examined to identify a common type of event for which many factors could be held constant. The decision was made to isolate events in which the vehicle was accelerating from rest (or very low speed) to approximately 65 kph, with several restrictions in order to reduce the effects of known and measurable influences. The events were required to have the following attributes:

- the initial speed is between 0 and 7 kph, and the final speed is between 60 and 67 kph,
- the final speed remains within 4.6 kph for at least 10 seconds,
- acceleration was sustained throughout the period from initial speed to the final speed,
- no vehicle was ahead to hinder the driver's choice of speed or acceleration (distance to preceding vehicle must remain at least 40 m away),
- the average grade cannot exceed 1%, either uphill or downhill, and
- the vehicle is not turning as it accelerates.

In addition, the fuel that is consumed is observed over both the acceleration period and a constant speed period that follows, until the total travel distance is 370 m. This distance is that needed for the slowest accelerating events to reach the required final speeds. By including the final, constant-speed period in the analysis, the comparison of events is a fair one that also uses the metric being used throughout this analysis, the volume of fuel consumed per unit distance traveled.

Over the entire data set, 1003 events met the criteria above. The fuel consumed varied from 0.041 to 0.099 gal, so that the fuel consumption rate varied from to 11.2 to 26.8 liters per 100 km. A histogram of the rate is shown in Figure 4.

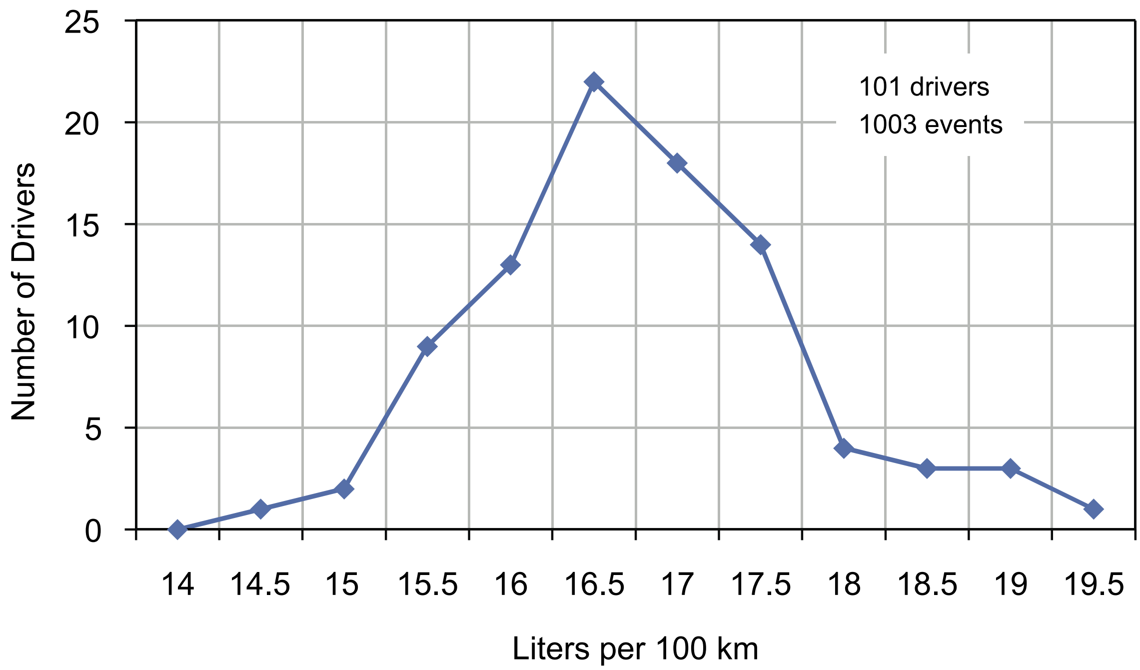

Figure 4. Individuals' fuel consumption rates during accelerating-from-rest events.

The events were then grouped by individual driver, and an average consumption rate was computed for each driver by averaging the fuel consumed (milliliters) for that driver's acceleration events. If there were at least three events for a driver, then the driver was included in a study set representing 101 of the drivers. The statistics of that study set are shown in Table 3. The mean of the individuals' means is 16.62 liters per 100 km traveled, with a standard deviation of 1.46 liters per 100 km. The driver averages corresponding to the 10^{th} and 90^{th} percentile for the study set are 7% below and 10% above the mean, respectively. This variation is slightly less than that for speed keeping. This may be due to the fact that the acceleration events were limited to relatively flat roads (average grade less than 1%), while the speed-keeping events were not.

Table 3
Individuals' mean fuel consumption rates for acceleration-from-rest events (liters per 100 km).

Number of events	Mean of individuals' means	Standard deviation	10^{th} percentile value (and difference from mean)	90^{th} percentile value (and difference from mean)
101 drivers 1003 events	16.62	1.46 (8.8% of mean)	15.40 (-7.4%)	18.29 (10.0%)

Conclusions

Fuel consumption rates were studied from a naturalistic driving data set employing a fleet of identical passenger vehicles with gasoline engines and automatic transmissions. One hundred and seventeen drivers traveled a total of over 342,000 kilometers (213,000 miles), unsupervised, using one of the experiment's instrumented test vehicles as their own. Continuous monitoring of hundreds of data signals, including fuel flow rate, provides a unique data set of driving behavior with a common vehicle.

The main findings are as follows:

(1) A substantial variation in the overall fuel consumption rate was observed. The average fuel consumption rate for the individuals was 10.1 liters per 100 km (equivalent to 23.6 mpg). The differences between the mean consumption rate and the fuel consumption rates for the 10^{th} and 90^{th} percentile drivers were 13 and 16 percent, respectively, of the mean value.

(2) Seventy eight percent of the fuel consumed occurred during times when the acceleration or deceleration did not exceed 0.55 m/sec^2 (i.e., at constant speed travel). Twenty percent of fuel consumed occurs during those relatively short durations in which acceleration exceeds positive 0.55 m/sec^2. The remaining two percent of fuel is used while the vehicle is decelerating or accelerating only slightly.

(3) The differences between the 10^{th} and 90^{th} percentiles and the mean for both speed-keeping events and accelerating-from-rest events were up to 10 percent.

While some of the obtained variation in fuel economy is likely due to uncontrolled or unmeasured factors, such as passenger and fuel weight, and wind, the data imply that the behavior of real-world drivers adds significant variation to fuel consumption rates. The present findings suggest the possibility of substantial potential gains in real-world efficiencies through modification of driver behavior itself (e.g., through training), or for electronic modulation technology between the driver's foot and the throttle to modify a relatively wasteful driver into a more efficient one.

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