Effects of Eco-driving on Commercial Motor Vehicle Driver Collision Risk

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Executive summary

This document examines the effect of commercial motor vehicle (CMV) drivers adopting fuel-efficient driving techniques (i.e., eco-driving) on the odds of being involved in hard-braking and stability control events, and collisions. Hard-braking and stability control events are recorded in response to sudden and large changes in speed and a vehicle deviating from its intended route, respectively. The total distance driven, the total number of trips taken by a driver during which they exceeded the posted speed limit (110 km/hr or 120 km/hr) at any point, and the ISAAC score (for companies that used the ISAAC instrument) are used as measures of fuel-efficient driving and exposure to quantify the effects on observed hard-braking events of a "fuel-efficient" driving style. For context, the ISAAC score is reported on a scale of 0 to 100 and measures the degree to which a driver is using an appropriate amount of engine power according to driving conditions.

Logit statistical models were developed to estimate the change in odds of a near-hit event or collision for drivers based on their driving style. The results revealed a one unit increase in the ISAAC score was associated with a 7%, 8%, 8%, and 4% reduction in the odds of having a hard-braking, hard left-turn, and hard right-turn events, and collision respectively. Also, driving in top gear with steady speeds close to 101 kilometers per hour (km/h) can significantly decrease stability control events by 34%. In addition, an increase in the driver's age as well as a 1% increase in the amount of time spent driving using cruise control reduced the number of hard-braking events by 9% and 3%, respectively. In conclusion, applying fuel-efficient driving techniques can improve the safety of CMV drivers as well as lead to fuel cost savings. Training for fuel-efficient driving of CMVs is available from Natural Resources Canada, including the SmartDriver for Highway Trucking online course.

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List of abbreviations

AMF | Accident Modification Factor
AASHTO | American Association of State Highway and Transportation Officials
CMV | Commercial Motor Vehicle
FHWA | Federal Highway Administration
HSM | Highway Safety Manual
Km/h | Kilometres Per Hour
Mi/h | Miles Per Hour
MPC | Model Predictive Control
ROC curve | Receiver Operating Characteristic curve
RPM | Revolutions Per Minute
VIF | Variance Inflation Factor
VMD | Vehicle Miles Driven

Introduction

Fuel economy for commercial vehicle fleets can be influenced through modified driving styles in terms of selected speeds, smooth driving, and route choice. Faster speeds increase fuel consumption, and the smoothness of driving refers to maintaining a relatively consistent speed as opposed to frequent accelerations and decelerations. Route choice can influence fuel economy due to the influence on predominant speeds and terrain. For example, routes with multiple intersections or many changes in elevation generally increase fuel consumption. In addition to the positive impacts resulting from fuel cost savings and fewer emissions, there are also possible safety benefits associated with a fuel-efficient, or eco-driving, driving style. This would be a specific benefit for fleet operators due to lower insurance costs and increased productivity. Training for fuel-efficient driving of CMVs is available from Natural Resources Canada, including the SmartDriver for Highway Trucking online course.

The current study was commissioned by Natural Resources Canada's Greening Freight Program and seeks to quantify the potential relationship between fuel-efficient driving and safety. The degree of fuel-efficient driving is measured using the ISAAC coach score, and safety outcomes are measured using near-hit events, and collisions. The analysis evaluates the relationship between the ISAAC score and the odds of being involved in both near-hit events and collisions using logit regression analysis. The data and analysis are tailored to Canadian fleets with long-haul, class 8 trucks.

This report summarizes the literature regarding aspects of fuel-efficient driving and safety as well as technology for assisting and monitoring the driving task. The remainder of the report documents the study methodology, analysis results, and conclusions.

Review of literature

A previous study (Hayworth and Symmons, 2001), discussed many factors related to fuel-efficient driving and the effects on greenhouse gases. The current literature review aims to build on that study, seeking to gain a further understanding of the potential safety outcomes of fuel-efficient driving. Table 1 shows the qualitative description of various factors and their potential impact on safety and fuel economy in that 2001 study.

Table 1 | Hayworth and Symmons, 2001: Summary of factors

Factor	Safety	Fuel Economy
Cruise control	Improve	Improve
Eco-drive training	Improve	Improve
Speed limiting devices	Improve	Improve
Fuel consumption feedback devices	Worsen (if causing distraction)	Improve
Replace traffic lights with roundabouts	Improve	Improve
Decreased residential speed limits	Improve	May worsen

Factor	Safety	Fuel Economy
Reduced open road speed limits	Improve	Improve
More freeways	Unclear	Improve
Decreased congestion	May reduce the total number of crashes but increase the average severity	Improve
Rebuild more direct/straighter/level roads	Improve	Improve

Vehicle speed

When fuel-efficient driving is considered, vehicle speed is likely the first factor that comes to mind. More fuel is required for a vehicle to travel at higher speeds. The following section discusses the impacts of vehicle speed on fuel economy, crash risk and crash severity.

Concerning the optimum fuel-efficient travel speed for an average vehicle, fuel consumption per distance travelled at a slower speed starts with a high consumption rate and then decreases as average speed increases, up to approximately 80 Kilometres per hour (km/h), then escalates with increasing speed. Related to commercial vehicles, Fender et al. (2011) state that truck fuel consumption increases significantly as speed rises above 55 miles per hour (mi/h), and 50 % of vehicle miles driven (VMD) for all combinations of trucks occurs at speeds above 55 mi/h (88.51 km/h).

Not only does vehicle speed impact fuel consumption, but traffic safety is also directly affected. Higher vehicle speeds affect safety in several ways. Increased speed reduces the time available for a driver to perceive and safely react to a dangerous situation, reduces lateral vehicle stability, increases the braking distance, and may affect tire grip on the pavement. A fact sheet available on the Federal Highway Administration (FHWA) website (SWOV, 2012) agrees that faster driving speeds reduce the likelihood of avoiding a crash.

Many studies have looked at the relationship between vehicle speed and crash risk. Most of them concluded" the relationship between speed and crash rate can best be described as a power function: the crash rate increases more rapidly as the speed increases and vice versa" (SWOV, 2012: p. 22). Several Scandinavian studies confirmed this relationship, especially between speed and injury severity when they examined the effects of increases and decreases in average travel speeds on the number of crashes due to changes in posted speed limits (Elvik, 2009; Elvik et al., 2004).

Haworth and Symmons (2001), citing research undertaken in the USA after raising the interstate highway speed limits, agreed there is overwhelming evidence that lower speeds result in fewer and less severe crashes. Finch et al. (1994) showed that an increase in mean speed of two to four mi/h (approximately three to six km/h) resulted in a 19-34% increase in fatalities. This roughly translates into an 8-9% increase in deaths on USA interstate highways for every one mi/h change in mean speed. The cited Finch et al. (1994) finding indicates that for every one km/h decrease in speed across the network, a 3% drop in crashes is expected. However, greater crash reductions per one km/h decrease in speed are achieved on residential and town center roads, and lower reductions are achieved on higher-quality suburban and rural roads.

Boodlal and Chiang (2014) cite a study that suggests a 5% decrease in average speeds leads to approximately a 10% reduction in injury crashes and a 20% reduction in fatal crashes (OECD, 2006). Farmer (2016) found that fatality rates increased as maximum speed limits were raised in 41 U.S. States. The results indicated that a five mi/h increase in each state's maximum speed limit was associated with an 8% rise in fatality rates on interstates and freeways and a 4% rise on other roads.

Further evidence that increased speed has an impact on the likelihood of more serious crash severities is provided by Kockelman et al. (2006), who determined that an increase from 55 to 65 mi/h speed limits raised the probability of a fatal injury by 24% and a change from 65 to 75 mi/h increased the probability by 12%. Malyshkina and Mannering (2008) also found that higher speed limits are associated with higher crash severity outcomes, including crashes that occurred on rural country roads, rural state routes, rural city streets, and rural U.S. routes. A 1% increase in posted speed was associated with an increased probability of a fatal crash up to 11.90% higher and up to 5.40% for injury crashes, depending on the route type.

Kockelman et al. (2006) also found that total (not just fatal or serious injury) crash rates rise with increasing speed limits albeit at a slower rate than fatal plus serious injury crashes. An increase from 55 to 65 mi/h increased total crash counts by 3.30% and from 65 to 75 mi/h by 0.60%.

Not only does the average speed influence crashes, but the variability between vehicle speeds also has an impact. Studies that have looked at speed variance mostly conclude that roads with a considerable speed variance[1] experience more crashes (Aarts and Van Schagen, 2006; Garber and Ehrhart, 2000; Forester et al., 1984; Zlatoper 1991). In this case, the greater distribution of speeds, the greater the number of interactions among vehicles which results in more passing maneuvers and opportunities for collision increase.

In summary, fuel consumption rates are associated with vehicle speeds such that, for an average vehicle, the fuel consumption rate per distance travelled is higher at slower speeds, decreases as average speed increases, up to approximately 80 km/h, and thereafter consumption rates again rise with increasing speed. Higher vehicle speeds are also associated with increased crash frequencies and greater crash severity.

Speed profile

In the context of fuel-efficient driving, the driving style is represented by the speed profile of a driver. The speed profile consists of time units with acceleration, deceleration, and constant speed phases. A fuel-efficient driving style has come to be referred to as eco-driving. This style minimizes the frequency and magnitudes of the acceleration and deceleration phases and aims to adopt a

[1] Speed variance explained: Imagine three vehicles on a section of road with 50, 70, and 90 km/h rates of speed and another section of road where all three vehicles are travelling at 70 km/h. The first scenario has a higher speed variance, and there is a good chance that drivers pass each other or overtake the slower vehicle, which increases the chance of a collision.

fuel-efficient constant speed. In contrast, an aggressive driving style is marked by frequent and extreme periods of acceleration and deceleration and inappropriately high speeds for conditions. As stated in Haworth and Symmons (2001), the speed profile during a trip is a more critical determinant of fuel consumption rate and emissions than the average speed for the trip.

There are many sources of eco-driving principles that share some basic common themes. Haworth and Symmons (2001: p. 25) cite Johannsson (1999) and Preben (1999) in listing the basic principles of eco-driving as:

- When heading off, one should shift up to second gear as soon as possible and then to higher gears at one-third to half-throttle.
- Engine speed should not exceed 3,000 RPM (or the level of highest torque).
- Drivers should look and plan so they can coast to traffic lights or intersections to reduce unnecessary braking, and the timing is such that the vehicle may not need to come to a complete stop.
- Driving to match the rhythm of the traffic.
- Use the upper gears as much as possible and keep engine speeds down.
- In vehicles of increased power and higher torque, the engine works more than changing a gear.
- Skip gears when it is appropriate.
- Keep engine idling to a minimum; and,
- No "warming-up" time is required when a car is first started."

These principles are primarily aimed at vehicles with non-automatic transmissions, although the principles related to minimizing unnecessary braking, driving with the rhythm of traffic, keeping idling to a minimum, and no warming-up time apply to all drivers. No warming-up time may not be recommended in colder climates.

The Energy Savings Trust (2016) in the U.K. discusses several driving techniques to maximize modern engine efficiency. Those directly related to driving style are shown in Table 2. Again, there is a focus on driving to reduce periods of acceleration and deceleration. Excessive speed is also mentioned, as high speeds require higher fuel consumption rates. In addition to fuel savings, a smooth driving style with less acceleration and braking reduces vehicle maintenance costs through less wear and tear on components, including brakes, clutches, and tires.

Table 2 | Examples of fuel-efficient driving (Energy Savings Trust, 2016: p. 3)

Drive smoothly	"Anticipate situations and other road users as far ahead as possible to avoid unnecessary braking and acceleration. Maintain a greater distance from the vehicle in front to regulate your speed, when necessary, without using the brakes."
Step off accelerator	"When slowing down or driving downhill, remain in gear but take your foot off the accelerator as early as possible. In most situations and for most vehicles, this will activate the fuel cut-off switch, reducing fuel flow to virtually zero."
Shift up early	"When accelerating, shift to a higher gear early, usually by around 2,000-2,500 rpm. Skip gears e.g., 3rd to 5th or 4th to 6th when appropriate"
Avoid excessive speed	"High speeds greatly increase fuel consumption."
Turn off/avoid idling.	"Turn off your engine if you expect to be stationary for more than a minute or so"

National Resource Canada (2021) provides similar guidance and suggests the adoption of five fuel-efficient driving techniques:

1. Accelerate gently
2. Maintain a steady speed
3. Anticipate traffic
4. Avoid high speeds
5. Coast to decelerate

There are many fuel consumptions estimates as a result of adopting an eco-driving style. Haworth and Symmons (2001), cite several sources: The U.S. Environmental Protection Agency's website (www.fueleconomy.gov/feg/drive.shtml) stated an expected 10% improvement in fuel economy by practicing fuel-efficient driving. Di Genova and Austin (1994; cited in Holmen and Niemeier, 1998) claimed that driver behaviour could alter average per-mile emissions by more than ten times in quantity. A British driver training organization has claimed that eco-driver training could save company fleets 10% in fuel and maintenance bills. Bongard (1995) claimed that experienced eco-drivers could save up to 30% on fuel consumption, and beginner eco-drivers could save on average one litre per 100 km compared to conventionally trained drivers. The Energy Savings Trust (2016) in the U.K. suggests eco-driving provides an average of around 15% savings, and a realistic long-term goal for a fleet might be between 3% and 6%. National Resource Canada (2021) suggests eco-driving savings of up to 25% without specifying vehicle type.

While there is a substantial discussion of the effects of driving style on fuel consumption in the literature, there is rarely a discussion of the impact on vehicle safety. Even where safety is discussed, there is limited data to support the mostly non-quantitative discussion. A driving style that does not speed too fast for conditions and avoids frequent and extreme acceleration and deceleration would be expected to reduce crash risk. Crash-based studies have found that "driving too fast for conditions or more than the posted speed limit" is a critical contributing factor in fatal crashes (Liu and Chen, 2009: p. 1).

However, while adopting eco-driving principles will reduce fuel consumption and may increase safety, an increase in safety is not always guaranteed. Parts of the road network require speed changes to minimize risk. For example, the design of corners, junctions, signals, lane merging, overtaking, and roundabouts. In this case, eco-driving can result in lower fuel usage while, at the same time, crash risk levels increase. The literature on such potential conflicts is discussed below.

A summary of the effects of driving style on both fuel consumption and safety, and available in-vehicle technologies, was provided by Vaezipour et al. (2015) and is shown in Table 3. Vaezipour et al. (2015: p. 3194) cited "Young et al. (2012), who identified potential conflicts between safety and eco-driving practices". For example, they discuss that driving in fifth gear with speed between 60 and 80 km/h, without stopping, will reduce fuel consumption and carbon dioxide emissions but may result in shorter following distances and thus an increased risk of rear-end collisions. It has also been argued that maintaining speed through intersections instead of slowing down increases the likelihood that a driver will fail to detect other road users. Further, distracted driving may result from in-vehicle eco-driving systems (Hayworth and Symmons, 2001). A study undertaken in 2004 by the Turku University in Finland, cited in the collision industry electronic commerce association (CIECA) in 2007, identified various situations where eco-driving practices may compromise the safety, including:

> Coasting through junctions and pedestrian crossings in an attempt to avoid stopping.

> Reducing distance between successive vehicles in a traffic lane (headway to the vehicle in front) maximizes speed homogeneity.

> Coasting prematurely disrupts the traffic pattern to the rear and increases the risk of a rear-end collision.

> Rapid acceleration to cruising speeds may result in shorter safety margins for the vehicle in front.

> Trying to stay in a high (fuel-efficient) gear, resulting in maneuvering at inappropriately high speeds (e.g., when cornering); and,

> Switching off the engine at short stops may lead to the steering wheel locking in some vehicles.

Table 3 | Aspects of eco-driving and impacts

Driving Parameter	Influence On		Example of In-Vehicle System Technologies
	Fuel Consumption	Safety	
Speed 60-80 km/h	Decrease fuel consumption	May increase the risk of crashes due to excessive speed	Speed recommendation Intelligent speed adaptation
Follow speed limit	May increase fuel consumption at low speeds	Decrease risk of crashes	
Cruising speed	Decrease fuel consumption	Decrease risky maneuvers	Cruise control
Smooth acceleration	Decrease fuel consumption	Decrease aggressive driving	
Smooth deceleration	Decrease fuel consumption	May increase risk of crashes due to the shorter distance between successive vehicles	
Sharp braking	Increase fuel consumption	May increase the risk of crashes due to rear-end collision	Haptic pedal feedback
Highest gear possible	Decrease fuel consumption	May lead to less control of the vehicle	Gear change advice Gear shift indicator
Idle time	Decrease fuel consumption (no more than ~30 sec)		
Safe distance between successive vehicles		Prevent rear-end collision (Time to Collision ~2-4 sec)	Collision avoidance/warning system
Lane Position		Decrease risk of crashes due to maintaining the car in the lane	Lane departure warning
Aggressive driving	Increase fuel consumption due to hard acceleration/deceleration	Increase risk of crashes	

Haworth and Symmons (2001) cite several studies that have examined the effects of eco-driving in terms of crash risk. Reinhardt (1999) analyzed the results of a training scheme instituted in a corporate fleet and found 35% fewer accidents, 22% higher vehicle miles driven (VMD) per crash, and 28% fewer fleet driver-induced crashes. Another company training program claimed an 11% fuel saving from 1990 to 1994 with a 35% improvement in crash rate (Smith and Cloke, 1999).

Dehkordie et al. (2019: p. 208) point out that "fuel-optimal behaviour is often difficult to implement due to traffic conditions and may lead to unsafe behaviour without proper constraints". Their research developed a methodology to find an ecological and safe (EcoSafe) driving behaviour for minimizing fuel use while respecting key safety constraints, namely time-to-collision. Others have explored driving styles obtained using the Model Predictive Control (MPC) framework (Lim et al., 2017; Luu et al., 2010; Bertsekas, 2005). MPC is an advanced methodology to control a process while satisfying constraints. This area of research will be important in the development of automated vehicles.

Route choice

Where alternate routes to reach a destination are an option, route selection can impact both fuel consumption and safety.

With respect to minimizing fuel consumption, a route that enables travel at a constant fuel-efficient speed and minimizes the need to accelerate and decelerate is optimal. This may mean avoiding congested roadways and routes with frequent intersections and driveways. Additionally, routes with curves or steep grades are less preferred due to the need to decelerate to keep lane position and the increased fuel demand for ascending vertical curves and positive grades. Recognizing some of these factors, National Resource Canada (2021) advises avoiding routes with crash delays or construction, avoiding routes through major cities and those with frequent traffic signals, intersections, and pedestrians, and using four-lane highways when possible.

Sivak (2012) states that different road types result in different average speeds and profiles of acceleration and deceleration. Consequently, fuel economy differs by road type. Sivak (2012) cites a Canadian study (Natural Resources Canada, 2009) that found that there can be a 9% or more fuel consumption savings on highways with a posted speed of 80 km/h (50 mi/h) or more than on other roads. Another cited study by Boriboonsomsin and Barth (2009) found that in a particular scenario with the same origin and destination but two alternative routes, a flat route yielded 15–20% better fuel economy than a hilly route. A cited study on fuel consumption for congested versus non-congested roads (Facanha, 2009) indicated that depending on vehicle type and road type, the reduction in fuel economy from service level A (no congestion and free-flow conditions) to service level F (highly congested with significant delays) can range from 20–40%.

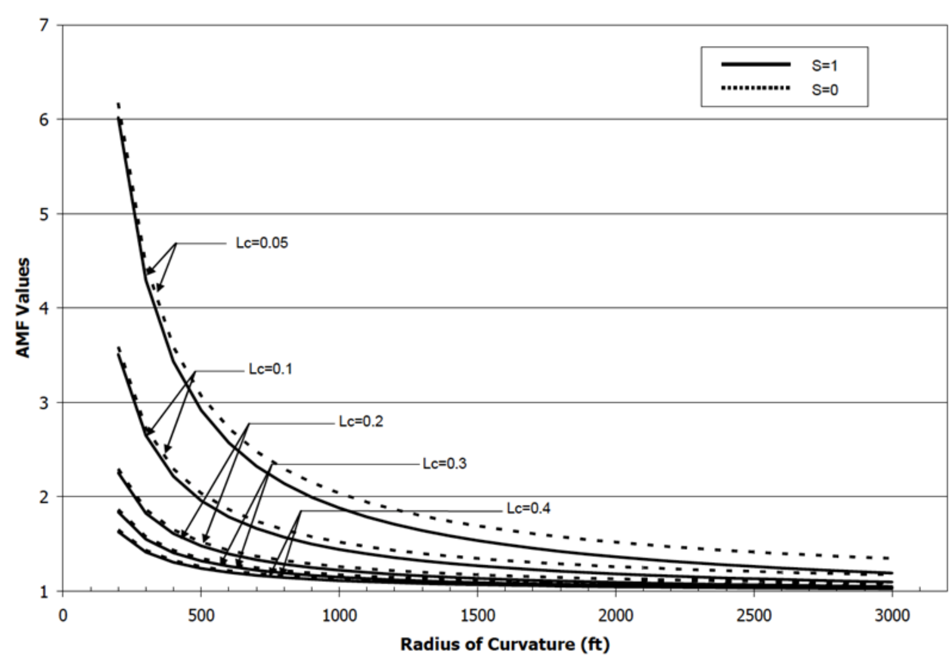
Regarding safety, travel on high-volume congested roadways creates opportunities for more frequent vehicle conflicts and crashes. Similarly, each driveway and intersection along a route generates additional chances for conflicts and crashes as vehicles entering and leaving the roadway often slow the movement of through traffic. The variance in speeds between through traffic and merging traffic can increase the risk of collision. The Highway Safety Manual (HSM) states that crash statistics show that although intersections constitute a small portion of the highway network, about 50% of all urban crashes and 25% of rural crashes occur near intersections (AASHTO, 2010). The American Association of State Highway and Transportation Officials (AASHTO's) A Policy on Geometric Design of Highways and Streets (i.e., the "Green Book") indicates that the number of crashes is disproportionately higher at driveways than at intersections (AASHTO, 2011).

The type of intersection being traversed also has a direct impact on safety as the expected crash frequency depends on intersection characteristics and the levels and patterns of traffic. Compared to unsignalized intersections, the safety benefits from signalization come from separating different vehicle maneuvers entering the intersection. Roundabouts also increase safety by reducing the speed of vehicles and changing the potential conflict points from crossing conflicts to merging conflicts, which are less severe. The Highway Safety Manual (AASHTO, 2010) indicates that converting an unsignalized intersection to a signalized intersection can be expected to reduce total crashes by 5% in urban environments and 44% in rural environments and, more importantly, reduce angle crashes, which are typically severe, by 67% in urban environments and 77% in rural environments. Estimates of safety effects show that converting signalized and unsignalized intersections to roundabouts can result in 48% and 44% reductions in total crashes, respectively; and 78% and 82% for fatal and injury crashes, respectively (Rodegerdts et al., 2010).

The geometric design of the roadway also has an impact on crash risk, with increased numbers of crashes expected in horizontal and vertical curves and on-road segments with steep grades. A greater number of crashes are expected on two-lane roads with a smaller horizontal curve radius and increased curve length, which can be estimated by applying an equation derived from statistical models and considering the curve length, radius, and presence of spiral transitions (AASHTO, 2010). Figure 1, taken from (AASHTO, 2010), illustrates the relationship between horizontal curve geometry and the Accident Modification Factor (AMF), which shows how crash risk changes by curve characteristics.

Figure 1 | Highway Safety Manual relationship between AMF and horizontal curve geometry

Exhibit 13-35: Potential Crash Effect of the Radius, Length, and Presence of Spiral Transition Curves in a Horizontal Curve



The Highway Safety Manual also provides estimates of the expected influence of grade on total crashes on road segments of rural two-lane roads. A grade of over 3-6% is associated with a 10% increase in crashes, and a grade over 6% with a 16% increase in crashes compared to a grade of 3% or less.

Hayworth and Symmons (2001) state that improved vertical curvature is estimated to lead to crash reductions of up to 52%. Improved horizontal curvature, for example, reconstructing the curve to make it less sharp or widening lanes and shoulders on curves, will also reduce crashes (Ogden, 1996; cited in Meers and Roth, 2001).

In summary, routes that allow for a constant fuel-efficient speed of travel and minimize conflicts with other vehicles can improve fuel efficiency and reduce crash risk. This can be accomplished by avoiding congested routes and/or routes with frequent intersections and horizontal and vertical curvature whenever possible.

Automated driving systems

Automated driving systems are developing at a rapid rate. Presently, there are already technologies available that can aid in adopting an eco-driving style, e.g., cruise control. In the long-term, semi-, and fully autonomous vehicles promise to increase fuel economy and improve safety. In the short term, using cruise control, adaptive cruise control, and speed limiters can improve driving styles by minimizing the frequency and magnitude of acceleration and deceleration and preventing high-speed travel, reducing the likelihood of a crash and lessen the severity of crashes when they do occur. Collision avoidance and lane-keeping systems are additional technologies that can improve safety but do not directly relate to fuel economy.

Some research does exist on the effects of automated driving systems that effect fuel consumption, but there is no quantitative information on the effects on crashes.

Haworth and Symmons (2001) cite a study that states that assuming cruise control is not used to exceed the speed limit, the use of cruise control can save an average of 5% in fuel (Wilbers, 1999). Sivak (2012) cites Edmunds (2005), estimating that using cruise control improves mileage at highway speeds by about 7%.

In-vehicle driver feedback systems may also promote eco-driving and safety. Vaezipour et al. (2015) discuss the technology, which includes dashboard displays of instantaneous and longer-term average fuel consumption rates, heads-up displays, and smartphone applications. The results show some in-vehicle systems can improve fuel efficiency without compromising safety. Several studies have been cited that show that these in-vehicle systems have positive effects on fuel consumption. Barth and Boriboonsomsin (2009) found that speed feedback (based on real-time, dynamic traffic sensing, and telematics data) via in-vehicle dashboard displays can reduce fuel consumption by 10-20%, depending on the context of the driving scenario. Similarly, 6.80% in fuel consumption reductions have been observed when bus drivers received instantaneous feedback on their driving from in-vehicle eco-driving systems (Stromberg and Karlsson, 2013). However, Haworth and Symmons (2001) advised that in-vehicle systems are not always safe to use if they cause a distraction to drivers.

In the longer term, driving automation may promise fuel efficiency and safety benefits. A cited study (Eisenstein, 2016)) states that a fully automated truck would see fuel consumption reduced by as much as 10% and could significantly reduce truck crashes to nearly zero. The report said that "truck crashes would plunge from a U.S. average of 222 per one million vehicle-miles-driven in 2000 to just eight by 2040" (Eisenstein, 2016: p. 01).

Schoettle and Sivak (2017: p. 16) discuss large-truck platooning as an eco-driving concept that will also positively benefit safety. They said that the concept of truck platooning involves two or more trucks being connected electronically while also possibly being controlled autonomously, driving in very close proximity to one another (one second or less separating vehicles)". The authors posit that fuel savings of up to 10% for each vehicle within a platoon may be expected.

Technology will also aid in route optimization as real-time traffic data can be used to alter routes to select the most fuel-efficient and safe route in real time.

Monitoring technologies

The availability of telematics technologies[2] Has great potential for understanding fuel efficiency and vehicle safety. Telematics provides a way to measure behaviours and provide feedback to drivers in real time. Existing telematics systems can provide a range of metrics, including speeds, engine RPM, deceleration and acceleration rates, and fuel consumption. Some of them have algorithms that incorporate many metrics to generate safety and/or eco-driving scores. These data could allow researchers to establish links between behaviours and their causes and outcomes.

As an example of research using telematics technology, Boodlal and Chiang (2014) used telematics to monitor various driver performance parameters, including unsafe events (sudden accelerations and hard-braking expressed as "yellow" and "red" events, depending on severity), speeding, engine RPM, and fuel economy. The purpose was to evaluate several interventions' effects on driver behaviour (providing information, feedback, training, and/or an incentive to modify driver behaviour). Researchers conducted a 10-month field evaluation that included installing telematics technologies in Class 8 trucks (defined as trucks having a gross vehicle weight rating of 33,001 pounds or more) in a combination of drivers with different scenarios, including whether they are unaware or aware of being monitored. Their findings indicated drivers of sleeper cabs showed a 55% reduction in less severe (yellow) unsafe events and a 60% reduction in more severe (red) unsafe events. Additional findings were that drivers of sleeper cabs (long-haul drivers) showed a 42% decrease in the percent of miles driving at > 65 mi/h, and drivers of day cabs showed a 33% decrease in the percent of miles driving at > 65 mi/h (i.e., speeding). Drivers of sleeper cabs showed a 48% decline in the percent of miles driven at > 1,500 rpm, and drivers of day cabs showed a 27% increase in the percent of miles driven at > 1,500 rpm. This may be due to drivers of day cabs normally returning to their base of operations each day, while drivers of sleeper cabs, who become attached to their vehicles, may not return to their base of operations for a week.

[2] A method of monitoring cars, trucks, equipment, and other assets using GPS technology and onboard diagnostics (OBD) to plot the asset's movements on a computerized map.

Concerning the interventions, providing driver incentives did not improve the safety metrics further than the previous combination of providing information, driver feedback, and training. As all of the above trends were taking place, fuel economy improved by 5.40% for drivers of sleeper cabs and by 9.30% for drivers of day cabs. The authors concluded that safe driving can be said to conserve fuel and reduce emissions. The authors also call for a longer study to collect crash data as an evaluation measure of safety.

Methodology

Objective

The objective of the study was to analyze the recorded driving behaviour of a group of Commercial Motor Vehicle (CMV) drivers and vehicles, notably long-haul class 8 trucks, to quantify the effects of fuel-efficient driving on safety. Safety is measured by recording the number of hard-braking events, involving sudden and large changes in speed (Steven Gursten, 2017), or the number of stability control events in which a vehicle deviates from the straight path and a driver must intervene to prevent a collision (National Safety Council, 2019). The measure of fuel-efficient driving uses the ISAAC score. The ISAAC score is reported on a scale of 0 to 100 and measures the degree to which a driver uses the appropriate amount of engine power according to driving conditions.

It is hypothesized that the adoption of an Eco-Driving style decreases the odds of CMV driver involvement in near-hit events and crashes.

Study population

The study population consisted of 2,531 long-haul class 8 vehicle drivers employed by commercial companies, with a primary focus on companies driving within Canada and those using the ISAAC instrument. Data were collected from three companies using the ISAAC instrument for the period from 19 January 2020 to 12 April 2022. Selected companies transported goods between Canada and anywhere across North America as well as internationally with a full range of transportation, logistics, warehousing, and distribution services. A total of 18,024,525 driving segments were analyzed for a total of 336,133,277 km of driving exposure.

In addition, this project also included data for one transportation company not utilizing ISAAC information for the timeframe June 2021 to October 2021. Instead, collected data included other eco-driving factors such as age/experience of drivers and driving style characteristics. A total of 103 drivers were analyzed for a total of 5,257,761 km of driving exposure, however, it was not possible to determine the number of driving segments. For this analysis, the effect of vehicle speed, using variables such as the highest gear and RPM was considered as measures of fuel-efficient driving techniques, or eco-driving and results are discussed separately.

Data collection

Near-hit events were defined in the study as hard-braking events. Hard-braking is a brake event only and is defined as “an event that triggers a black box in a commercial truck to record a sudden change in speed that meets some pre-set threshold by the manufacturer" (Steven Gursten, 2017: p. 1). The number of hard-braking, hard left-turn, and hard right-turn events, of each driver were summed for the study period. Both lateral and longitudinal accelerometer axis were recorded individually. The thresholds for these events were 0.35g which is 3,43 m/s2 (1g = 9.81 m/s2). A hard-brake is a longitudinal g force smaller than -0.35g (a negative longitudinal g force is a deceleration). A hard left-turn is defined as a lateral g force smaller than -0.35g (a negative lateral g force is a leftward acceleration). A hard right-turn is defined as a lateral g force greater than 0.35g (a positive lateral g force is a rightward acceleration) (ISAAC Instruments Incorporated, 2021).

The driving performance scores of drivers who followed the guidelines of ISAAC's Coach for eco-driving were also recorded. The ISAAC Coach provides real-time feedback to drivers through a tablet and evaluates whether the appropriate amount of engine power was used according to the driving conditions. These conditions can be impacted by load, slope, shape, and type of trailer, wind, temperature, rain and snow, and rolling and mechanical resistance (ISAAC Instruments Incorporated, 2021). ISAAC's criteria present a score out of 100 based on driving performance at the end of a driving segment, with a more fuel-efficient driving style receiving a higher ISAAC score. The overall ISAAC score for each driver during the study period was calculated using a weighted mean across all trips with the weights according to the distance travelled.

To account for exposure, the total distance traveled in the study period was also recorded. This variable was divided by 10,000 for ease of model interpretation.

Additional variables collected include the total number of segments a driver took on which at any point they exceeded the posted speed limit (110 km/hr or 120 km/hr). In this regard, this measure is a count of occurrences per segments. Events are triggered when the speed exceeds 110 and 120 km/h. For instance, if the vehicle exceeds 120 km/h, slows down and, again, goes exceeds 120 km/h again few seconds later, it counts as two occurrences, whereas if a truck consistently exceeds 120 km/h for an hour, it counts as one.

Prior to data collection a data-sharing and confidentiality agreement was prepared and signed by all participating companies agreeing to provide data in order to protect the privacy, confidentiality, and ownership of company data.

Data analysis

Logit models were developed in the Stata software to explore the impact of fuel-efficient driving on the odds ratio of near-hit events and collisions. The odds ratio can be interpreted as the probability of an event occurring when the factor of interest is present, divided by the probability when the factor is not present. For example, companies may be interested in the odds ratio of crash involvement by drivers older than age of 25 compared to drivers aged 24 and younger. If drivers aged 24 and younger represent the baseline and the odds ratio for drivers aged 25+ is 0.70 this means older drivers are 30% less likely to be crash-involved. The linear relationship between the explanatory variables and a binary response variable, including near-hit and no near-hit collisions can be written in the following equation where ℓ is the log-odds, X_i is independent variables and β are coefficients of parameters of the model (Ma et al., 2009):

$$\ell = Log\,\frac{P}{1-P} = \beta_0 + \beta_1 X_1 + \beta_2 X_2 \qquad (1)$$

This formula quantifies the percentage of change in odds ratio by one unit increase of an explanatory variable. In this study, the logit models quantified the odds ratio of a near-hit event or collision by one unit increase of an explanatory variable. Explanatory variables include the weighted mean of the ISAAC score, total distance driven per 10,000 km, and the total number of driving segments in which a driver exceeded the posted speed limit (110 km/hr or 120 km/hr) at any point.

In developing the logit models, various thresholds regarding the number of hard-braking events (ranging from 0 to 4) and collisions (ranging from 0 to 2) were used to define higher-risk driving. For instance, a threshold of one means that if a driver has more than one hard-braking event in the studied period from January 2020 to April 2022, it can be assumed there was a higher crash risk for that driver.

This study used a variance inflation factor (VIF) to check the collinearity between explanatory variables since this issue will reject the assumption of independency in the model. Also, the best-fitted models were chosen based on several measures of goodness-of-fit, including a maximum value of Pseudo R^2, area under the ROC curve, and correctly classified (%). The area under the ROC curve describes the overall performance of a classification model in which values close to 1 represent an accurate model, and values less than 0.50 are not acceptable (Provost and Domingos, 2000; Mujalli, López, and Garach, 2016).

Results

The models revealed that a one unit increase in the weighted mean of the ISAAC score (ranging from 0% to 100%; 100% means the driver followed ISAAC coach's advice in all situations) was associated with a 7% reduction in the odds of having a hard-braking event, an 8% reduction in the odds of a hard left-turn event, and 8% reduction in a hard right-turn event.

In addition, an increase of 10,000 km in total distance traveled produced a 51% increase in the odds of having a hard-braking event, a 6% increase in a hard left-turn event, and a 6% increase in hard right-turn event. The Odds ratios for the speeding variables did not show any statistically significant relationship with hard-braking events or collisions.

With respect to collisions, the results showed ISAAC's coach reduced the odds of collisions by 4% significantly. Logically, the odds ratio for the distance variable is positive and statistically significant. In this regard, the model indicated an increase in distance traveled of 10,000 km is associated with a 7% increase in the probability of having a collision.

The logit regression results for hard-braking, hard left-turn, and hard right-turn events using different thresholds starting with zero and ending with four are shown in Table 4. Results for collisions are presented in Table 5 using thresholds from zero to two. These tables provide the estimated Odds Ratios and p-values for each of the independent variables included in the models as well as the measures of goodness-of-fit. Note that p-values less than 0.05 indicate the effect of explanatory variables is statistically significant at the 95th percentile confidence limit. The final selected models (based on the goodness-of-fit measures) are shown by the shaded rows. Models were also estimated for a combined dataset with all three companies, applying a zero-event threshold for hard-braking, hard left-turn and hard right-turn events.

Table 4 | Results of logit regression for different thresholds

Near-hit collisions	Cut-point Threshold*	WM ISAAC**		Sum distance (per 10,000 km)		Sum Speeding110		Sum Speeding120		Pseudo R2	Area under ROC curve	Correctly classified (%)
		Odds	P>|z|	Odds	P>|z|	Odds	P>|z|	Odds	P>|z|			
Hard-braking	0	0.93	0.00	1.51	0.00	1.00	0.28	1.01	0.81	0.36	0.92	92.92
	1	0.92	0.00	1.36	0.00	1.00	0.11	1.00	0.79	0.34	0.90	88.81
	2	0.91	0.00	1.29	0.00	1.00	0.03	1.01	0.38	0.34	0.89	87.03
	3	0.91	0.00	1.25	0.00	1.00	0.00	1.01	0.26	0.33	0.88	84.46
	4	0.90	0.00	1.23	0.00	1.00	0.01	1.01	0.12	0.33	0.88	83.95
hard left-turn	0	0.92	0.00	1.06	0.00	1.00	0.86	1.00	0.93	0.10	0.71	67.06
	1	0.92	0.00	1.05	0.00	1.00	0.51	1.00	0.38	0.09	0.70	64.61
	2	0.92	0.00	1.04	0.00	1.00	0.95	1.00	0.37	0.09	0.70	65.48
	3	0.92	0.00	1.04	0.00	1.00	0.85	1.00	0.29	0.09	0.70	68.96
	4	0.91	0.00	1.04	0.00	1.00	0.06	1.00	0.15	0.09	0.70	72.20
hard right-turn	0	0.92	0.00	1.06	0.00	1.00	0.34	1.01	0.04	0.10	0.72	71.06
	1	0.91	0.00	1.05	0.00	1.00	0.31	1.00	0.07	0.10	0.71	66.51
	2	0.91	0.00	1.05	0.00	1.00	0.38	1.00	0.17	0.10	0.72	65.16
	3	0.91	0.00	1.05	0.00	1.00	0.32	1.00	0.18	0.10	0.71	65.32
	4	0.91	0.00	1.04	0.00	1.00	0.91	1.00	0.29	0.09	0.70	67.58

* More than this value assumed a driver exposed to risky events (e.g., hard-braking) during the studied period

** Weighted mean of ISAAC scores for all segments driven during the studied period

Table 5 | Odds of having collisions- logit regression results

Company	Cut-point Threshold*	WM ISAAC**			Sum distance (per 10,000 km)			Pseudo R2	Area under ROC curve	Correctly classified (%)
		Odds	95% CI	P>|z|	Odds	95% CI	P>|z|			
Total	0	0 .96	[0 .95, 0.98]	0.00	1.07	[1.06, 1.08]	0.00	0.12	0.73	66.76
	1	0.95	[0 .93, 0.97]	0.00	1.06	[1.05, 1.08]	0.00	0.10	0.72	76.63
	2	0.95	[0.92, 0.98]	0.00	1.06	[1.04, 1.08]	0.00	0.08	0.72	89.76

* More than this value assumed a driver exposed to risky events (e.g., hard-braking) during the studied period

** Weighted mean of ISAAC scores for all segments driven during the studied period

This project also included data for a transportation company for the timeframe (June 2021 through October 2021) that collected data regarding other eco-driving factors like age/experience of drivers and driving style characteristics, but that did not utilize ISAAC information. A total of 103 drivers were analyzed for a total of 5,257,761 km of driving exposure. In this instance, the effect of vehicle speed, using variables such as the highest gear, and engine revolutions per minute (RPM) was considered as measures of fuel-efficient driving techniques, or eco-driving. Data were analyzed to estimate the odds of hard-braking and stability control events as proxies of collisions. The results of a logit model showed that driving in top gear with steady speeds close to 101 Kilometres per hour (km/h), which is a fuel-efficient speed, can significantly decrease the number of stability control events by 34%. Furthermore, an increase in the driver's age, and a 1% increase in the use of cruise control during the amount of time spent driving were associated with a 9% and 3% reduction in the odds of having a hard-braking event, respectively. It was also demonstrated that speeding and longer distances driven by drivers (per 10,000 km) can increase the risk of having a stability control event by 4% and 55%, respectively.

Conclusion & discussion

Research has demonstrated that using tactics such as shifting up sufficiently early or downshifting as late as possible, and using a driver assistance system (e.g. cruise control) can enable truck drivers to reduce fuel consumption by an average of 5% (Eco-Drive, 2021). This study investigated whether eco-driving techniques can have a positive impact on safety by reducing likelihood of experiencing a near-hit event, as measured by stability control, hard-braking, hard left-turn, and hard right-turn events or a collision.

Hard-braking events can increase the risk of collisions. Hard-braking frequently may indicate a driver is following too-close at an unsafe distance which reduces safety for all road users (Kevin Aries, 2021). In addition, "excessive occurrences of hard-braking can cause vehicle brakes to overheat, damaging the metal components or glazing brake pads. This makes them less effective and reduces their lifespan, ultimately putting the driver in danger of not being able to stop when needed" (Kevin Aries, 2021: p. 1).

The ISAAC score is recorded based on a driver's performance (McDaniel, 2022). Driving in a manner that results in a high ISAAC score can result in fuel cost savings of up to 15% and lead to increased safety (Ashley Coker, 2022). Regarding the importance of this subject, the current study described the benefits of ISAAC coach in reducing hard-braking events and collisions.

The results of logit regression models showed the results are by and large consistent, irrespective of the threshold used to define unsafe driving. The analysis of real-world driving data demonstrated an increasing ISAAC score was associated with fuel-efficient driving. It was also associated with significant reductions in the odds of all types of hard-braking events and collisions.

The models also logically showed the odds of all hard-braking events and collisions increased with an increase in distance traveled. This finding illustrated the role of exposure in increasing collision risk. In other words, the more mileage a person drives, the greater their risk of eventually having a collision. This fact was confirmed for both female and male drivers (Rolison and Moutari, 2018).

With respect to fuel-efficient driving, or eco-driving consistent with the ISAAC guideline, less time spent speeding, more use of cruise control features and more time spent in top gear (capped at 101 km/h in cruise control or 105 km/h in regular driving mode) were all associated with a lower risk of experiencing a near-hit event. Other findings showed that increased age of CMV drivers was associated with a reduced risk of collisions.

In conclusion, adopting an eco-driving style would be expected to reduce crash risk and lead to savings in insurance costs and increased productivity. Training for fuel-efficient driving of CMVs is available from Natural Resources Canada, including the SmartDriver for Highway Trucking online course.

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