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Safety impacts due to the incompatibility of SUVs, minivans, and pickup trucks in two-vehicle collisions

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ABSTRACT

This research sets out to estimate the effects of vehicle incompatibility on the risk of death or major injury to drivers involved in two-vehicle collisions.

Based on data for 2,999,395 drivers, logistic regression was used to model the risk of driver death or major injury (defined has being hospitalized). Our analyses show that pickup trucks, minivans and sport utility vehicles (SUVs) are more aggressive than cars for the driver of the other vehicle and more protective for their own drivers. The effect of the pickups is more pronounced in terms of aggressivity. The point estimates are comparable to those in the Toy and Hammitt study [Toy, E.L., Hammitt, J.K., 2003. Safety impacts of SUVs, minivans, and pickup trucks in two-vehicle crashes. Risk Analysis 23, 641–650], but, in contrast to that study, we are now able to establish that a greater number of these effects are statistically significant with a larger sample size.

Like vehicle mass and type, other characteristics of drivers and the circumstances of the collision influence the driver's condition after impact. Male drivers, older drivers, drivers who are not wearing safety belts, collisions occurring in a higher speed zone and head-on collisions significantly increase the risk of death. Except for the driver's sex, all of these categories are also associated with an increased risk of death or of being hospitalized after being involved in a two-vehicle collision. For this risk, a significant increase is associated with female drivers.

1. Introduction

Since the early 1990s, the light duty vehicle fleet has seen major change in North America with amazing growth in sport utility vehicles (SUVs), and an appreciable increase in the number of pickup trucks and minivans. These three types of vehicles form a category generally known as light trucks and vans (LTV). For example, Fig. 1 shows this trend in the fleet in Canada between 1989 and 2002. We point out that SUVs have seen dramatic growth (287%), followed by minivans (160%) and pickup trucks (34%). Over the same period, the number of passenger cars fell by 2%.

This major change in the vehicle fleet composition is thought to affect road safety. There is concern about the safety of occupants involved in collisions between two light duty vehicles of differing geometry and mass, a phenomenon better known as "vehicle incompatibility." According to Gabler and Hollowel (1998), a vehicle's incompatibility is the combination of its self-protective capacity and aggressivity when involved in collisions with another vehicle. Self-protection centres on a vehicle's chances of shielding its occupants in a collision, whereas aggressivity is measured by causality affecting the occupants of the other vehicle in the collision. As the relative composition of the fleet of vehicles is altered, negative effects on road safety might appear.

A literature review reveals that a number of factors increased by this major change in the car fleet actually affect passenger safety in collisions. A number of studies acknowledge the influence of mass and geometry on the risk incurred by passengers: the difference in masses increases the self-protection and aggressivity of the heavier vehicle, whereas geometric incompatibility (e.g., of a passenger car versus an LTV) generally penalizes the car driver. These factors were cited in recent studies by O'Neill and Kyrychenko (2004), Acierno et al. (2004), Broyles et al. (2003), Toy and Hammitt (2003), Mayrose and Jehle (2002), Joksch (2000), and Farmer et al. (1997).

The literature review also shows that a number of control variables must also be considered to fully gauge incompatibility. For example, the literature shows women as more at risk of major injury than men and the use of safety devices (belts and/or airbags) remains salutary for both sexes. These factors were cited in recent studies by Ulfarsson and Mannering (2004), Dissanayake and Lu (2002), Bedard et al. (2002), and Mercier et al. (1997).

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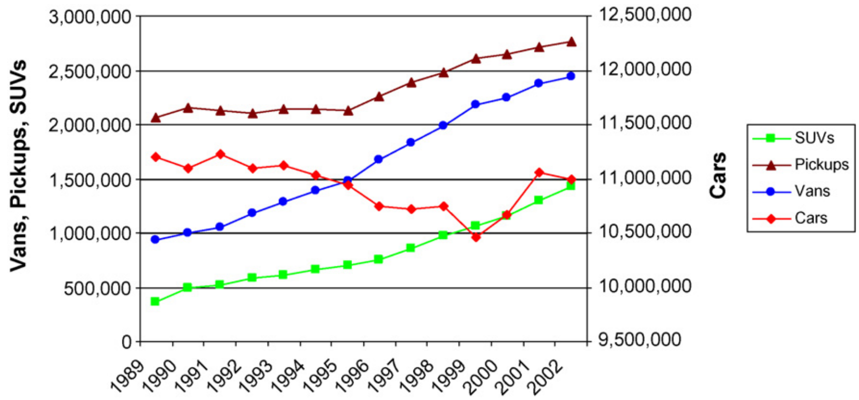

Fig. 1. Census of light duty vehicles (passenger cars and LTVs) in Canada between 1989 and 2002. This figure uses data from the *Canadian Vehicle In Operation Census* database.

The aim of this study is to estimate the LTV effects on road safety by comparing them with the effects of passenger cars, using an analysis of the risk of death and/or hospitalization to the drivers of vehicles involved in two-vehicle collisions. We decided to focus our analysis only on drivers because information on drivers in administrative databases is in general more complete, and secondly to be able to compare our results to other studies that also focused only on drivers, and in particular with those of Toy and Hammitt (2003), since their study had the same objectives as ours and the methodology used is comparable on several levels. However, our larger sample size allows us to more accurately pinpoint the statistical significance of the estimated effects and to use models that make more precise distinctions between the various types of vehicle incompatibility.

2. Methodology

The data used in our study come from Transport Canada. They were chosen from the NCDB (National Collision Database). This database contains information on all collisions reported by police in Canada. This made it possible to analyse two-vehicle collisions occurring between 1993 and 2001 in seven Canadian provinces or territories: Alberta, Prince Edward Island, Ontario, Quebec, Newfoundland, Saskatchewan and Yukon (the number of years with available data for our analyses varied by province: minimum of 5 and maximum of 9 years). From this database, we were able to extract information about the drivers involved in two-vehicle collisions. These collisions exclude the ones involving motorcycles, bicycles, snowmobiles, or all-terrain vehicles, and those where the type of one or both vehicles involved was missing. Observations where the severity of the injuries of the driver is missing were also deleted from our sample. Note that most rollovers are not included because they usually involve single vehicle collisions which are not considered here. It is however possible that a vehicle could rollover after an initial contact with another vehicle and those few cases are included in our sample. The resulting number of observations that were used is 2,999,395.

In addition to police report data, we used the vehicle identification number (VIN) to obtain the vehicle characteristics such as the body style and weight (i.e. base weight of the vehicle series) to classify them into six vehicle types: passenger car, SUV, pickup truck, minivan, heavy truck and bus). Table 1 gives the Polk codes for body styles associated with each vehicle type considered in our analyses.

Unlike Toy and Hammitt (2003), who used only one criterion variable (the risk of severe injury or death in a collision), we will consider two criterion variables: the risk of death in a two-vehicle collision and the risk of major injury or death. Both criterion variables being binary, we will use logistic regression to model them. It is important to note that the severity of injury in our study is extracted from police reports. So major injury is reported if the driver is hospitalized following the collision and death is reported if the driver died within 30 days (8 days in Quebec). Toy and Hammitt (2003) used the Abbreviated Injury Scale (AIS) to determine the drivers' injury severity in their study. Drivers with AIS greater or equal to 3 were considered having a serious injury. Although a non-seriously injured driver could be hospitalized, there is a strong association between major injuries and hospitalization.

The first independent variable of interest in our study is the driver's vehicle type, which will allow to determine the self-protection each vehicle type gives the driver. The second independent variable is the type of the other vehicle involved in the collision, which will allow to determine the aggressivity of these vehicles. In addition to geometric incompatibility, we can use a third independent variable to evaluate the effect of the incompatibility caused by difference in vehicle mass. This variable will be the mass ratio of both vehicles involved in the collision coded into 5 categories: the driver's vehicle is at least two times lighter (0, 0.5], two times to 20% lighter (0.5, 0.8], the difference is less than 20% (0.8, 1.2], 20% to two times heavier (1.2, 2] and at least two times heavier (2, +∞).

The control variables used in earlier studies and available from our database are the driver's sex, the driver's age (classified in four groups: under 25, 25–44, 45–64, and 65 and over), whether or not a safety belt was worn, maximum authorized speed where the collision occurred (under 50 kph, 50–60 kph, 70 80 kph, 90 kph and 100 kph), and impact configuration (head-on, rear-end, side-swipe, etc.). We will use all these variables in our model.

Table 1
Classification of the vehicles based on the body style Polk codes from the vehicle identification number (VIN)

Vehicle type	Polk codes from VIN for body style
Car	2D 2H 2L 2P 2T 3D 3P 4D 4H 4L 4P 5D CP CV[a] HR HT IN LB LM NB RD SD SW[a]
Pickup truck	3B 3C 4B 4C CB FB[a] PK
Minivan[b]	SV VN
SUV	CV[a] LL SW[a] UT
Heavy Truck	AC CC CM DP DS FB[a] FT GG GL TB TL TM
Bus	BU

[a] CV, SW, FB: these body style Polk codes appear in two vehicle types; thus, the vehicle weight and/or the vehicle model from VIN and the vehicle type variable recorded in the police report were used for these cases to classify them into the appropriate category.

[b] The category minivan includes full-sized vans.

Table 2
Distribution of the variable for driver injury severity

Injury severity	Frequency	Percentage (%)
None	2,665,239	88.86
Minor (no hospital admission)	310,575	10.35
Major (hospitalization but no death within 30 days)	20,291	0.68
Fatal (death within 30 days)	3,290	0.11
Total	2,999,395	100.00

For the mass ratio and each other control variable, a category representing the missing values was created and included in the logistic regression models. This allowed us to keep the 2,999,935 observations by estimating the effect of having a missing covariate. However, although it is important to control for them, the estimated effects corresponding to the missing category are not of interest and are thus not presented in Section 3.

The readers must keep in mind that only collisions reported by police are accounted for here. Collisions with property damage only are less likely to be reported by police, so the percentage of uninjured drivers among all possible collisions is higher than the one reported in Section 3. Other potential biases and possible limitations of this study due to the use of police-reported data will be discussed at the end of Section 3 and also in Section 5.

3. Results

3.1. Descriptive analyses

Table 2 shows the distribution of our study's target variables. A total of 3290 (0.11%) drivers died after being involved in a two-vehicle collision, 20,291 (0.68%) were hospitalized and 310,575 (10.35%) had minor injuries. The conditional distributions of the drivers' injury severity that reflect the association with the different independent variables are presented in Tables A1–A3 in Appendix A. The percentages of drivers killed and hospitalized after being involved in a two-vehicle collision is higher when they were driving a car or a pickup truck or when they were colliding with a heavy truck, a bus or a pickup truck (Table A1). Furthermore, the lower the mass ratio, the higher is the percentage of drivers killed and hospitalized (Table A1).

In the database, the percentage of male drivers who were killed in two-vehicle collision is higher (0.12%) than the percentage of female drivers killed (0.09%). The percentages of female drivers hospitalized (0.82%) and having a minor injury (14.90%) are however higher than those for male drivers (0.62% and 8.25% respectively, Table A2). Furthermore, 2.69% of unbelted drivers were killed and 7.71% hospitalized compared to 0.26% and 1.94% respectively for belted drivers. Note that the information on safety belt is missing for 70% of the drivers in the database (Table A2). The missing information on safety belt occurs mainly for crashes with property damage only (PDO). In many provincial jurisdictions in Canada police officers are not required to fill out the fields on the characteristics of vehicle occupants in their report for PDO crashes.

The percentages of drivers being killed and/or hospitalized increase with the posted speed limit, except for the last category of 100 kph which generally corresponds to divided highways in Canada (Table A3). Head-on collisions followed by right-angle collision with the main impact on the driver's side are the ones with the highest percentages of drivers killed and hospitalized (Table A3). It is important to note that information available in the administrative databases from police reports in Canada usually only mention the configuration of the collision as a whole and do not distinguish between the struck and striking vehicles. For example, we usually do not know if the struck vehicle involved in a right-angle collision was impacted in the front, the driver side or the passenger side. However, in 10% of all right-angle collisions, we were able to determine from the available information in the databases that the struck vehicle was impacted on the driver side.

3.2. Logistic regression analysis results

We begin with the results for risk of death and go on to present the results for risk of being hospitalized or being fatally injured. In the province of Quebec, a driver was reported as being fatally injured if he died within 8 days after the collision. The other provinces used 30 days. We thus performed two logistic regressions for the risk of death: one with the drivers from Quebec and one without. Since the results were essentially the same, only the results where the province of Quebec was included are presented.

3.2.1. Driver death risk results

The second column of Table 3 presents the odds ratios (ORs) obtained for the logistic regression model in terms of probable risk of death for drivers involved in two-vehicle collisions. ORs significantly different than 1 at the 5% level are printed in bold font. Note that this criterion variable was not used by Toy and Hammitt (2003) because the likelihood of dying in a two-vehicle collision reported by police is so small (about 0.11%: see Table 2) that a large sample size is needed to estimate the model's parameters.

LTVs are differing significantly from passenger cars in terms of aggressivity and self-protection. Compared to car drivers, the probability of fatal injury (given that the collision would be reported by police) is reduced by about 34% for minivan drivers (OR = 0.66), 29% for drivers of SUVs (OR = 0.71), and 26% for drivers of pickups (OR = 0.74). As to aggressivity, drivers colliding with a pickup truck rather than a car are 2.72 times more likely to die. Drivers colliding with SUVs and minivans are, respectively, 2.12 and 1.83 times more likely to die than if they had collided with cars. Heavy trucks and buses are very aggressive (OR = 4.06 for trucks and 3.89 for buses) and self-protective (OR = 0.15 for trucks and 0.13 for buses).

With respect to mass ratio as such, we see this variable has a significant effect: the higher the ratio, the smaller the risk of dying in the collision. For example, the driver of a vehicle with a ratio under 0.5 is 11 times (2.13/0.18) more likely to die than the driver of the other vehicle (provided all other variables for these two drivers are identical).

With respect to the variables introduced to control for the driver characteristics, we first point out that the risk of death for men rose by 23% compared to the risk for women. As for age, we note first that there is no significant difference between the under 25 and 25–44 age groups, but the risk of death increases with age thereafter. Finally, when it is mentioned in the police report that the driver was not wearing a safety belt, the risk of death increases greatly (8.96 times).

As vehicles' exact speed is not available in the database, we emulated Joksch (2000) in using the speed limit as a proxy variable. The results show the speed limit as a highly significant factor in estimating drivers' risk of death. We see right away that a collision where the speed limit is less than 50 kph reduces the drivers' risk of death by 71% (OR = 0.29) compared to the reference category (speed limit of 50–60 kph). Drivers colliding in 70–80 kph zones are 6.79 times more likely to die and this risk increases up to a factor of approximately 12.5 in 90 kph or 100 kph zones.

We finally control for the configuration of the collision in this model. It confirms that head-on collisions are the most deadly followed by right-angles.

Table 3
Logistic regression results for drivers' risk of death and driver's risk of hospitalisation or death (significant odds ratio are in bold font).

N = 2,999,935	Odds ratios (95% confidence intervals)	
	Risk of death	Risk of hospitalization or death
Driver's vehicle type		
Car	Ref	Ref
Pickup	**0.74 (0.66–0.82)**	**0.86 (0.83–0.90)**
Minivan	**0.66 (0.57–0.78)**	**0.81 (0.76–0.85)**
SUV	**0.71 (0.57–0.88)**	**0.84 (0.78–0.91)**
Heavy truck	**0.15 (0.11–0.20)**	**0.28 (0.25–0.32)**
Bus	**0.13 (0.05–0.36)**	**0.20 (0.14–0.27)**
Type of other vehicle		
Car	Ref	Ref
Pickup	**2.72 (2.46–3.02)**	**1.65 (1.59–1.71)**
Minivan	**1.83 (1.59–2.10)**	**1.24 (1.18–1.30)**
SUV	**2.12 (1.78–2.54)**	**1.26 (1.18–1.35)**
Heavy truck	**4.06 (2.67–6.16)**	**2.07 (1.70–2.51)**
Bus	**3.89 (1.49–10.12)**	1.18 (0.70–1.98)
Mass ratio		
Less than 0.50	**2.13 (1.55–2.93)**	**1.72 (1.51–1.97)**
0.50–0.80	**1.53 (1.33–1.77)**	**1.18 (1.12–1.24)**
0.80–1.20	Ref	Ref
1.20–2.00	**0.53 (0.42–0.66)**	**0.73 (0.68–0.77)**
More than 2.00	**0.18 (0.05–0.74)**	**0.45 (0.34–0.60)**
Driver's sex		
Female	Ref	Ref
Male	**1.23 (1.14–1.34)**	**0.90 (0.87–0.92)**
Driver's age		
Under 25	1.04 (0.94–1.15)	1.00 (0.96–1.03)
25–44	Ref	Ref
45–64	**1.51 (1.37–1.66)**	**1.14 (1.11–1.19)**
65 and +	**3.58 (3.23–3.97)**	**1.74 (1.67–1.82)**
Safety belt		
No belt	**8.96 (8.12–9.89)**	**5.21 (4.97–5.47)**
Safety belt	Ref	Ref
Authorized speed		
Less than 50 kph	**0.29 (0.15–0.56)**	**0.48 (0.42–0.55)**
50–60 kph	Ref	Ref
70–80 kph	**6.79 (5.96–7.73)**	**3.09 (2.96–3.21)**
90 kph	**12.51 (10.9–14.3)**	**5.10 (4.86–5.35)**
100 kph	**12.68 (10.8–14.9)**	**3.99 (3.74–4.26)**
Collision		
Rear-end	**0.13 (0.11–0.16)**	**0.30 (0.28–0.31)**
Side-swipe (same dir.)	**0.25 (0.20–0.31)**	**0.24 (0.22–0.26)**
Left turn conflict (same dir.)	**0.29 (0.21–0.40)**	**0.64 (0.58–0.69)**
Right turn conflict (same dir.)	**0.15 (0.08–0.26)**	**0.39 (0.34–0.45)**
Head-on	**5.08 (4.60–5.61)**	**2.91 (2.80–3.03)**
Left turn conflict (diff. dir.)	**0.53 (0.46–0.62)**	**0.68 (0.66–0.71)**
Right turn conflict (diff. dir.)	0.89 (0.51–1.55)	1.01 (0.83–1.23)
Right-angle (side undetermined)	Ref	Ref
Right-angle (driver side impact)	**2.33 (1.96–2.76)**	**1.57 (1.47–1.68)**
Other	0.75 (0.56–1.01)	**0.68 (0.61–0.76)**

3.2.2. *Drivers' death or hospitalization risk results*

The third column of Table 3 shows the results of the logistic regression model in terms of risk of death or hospitalization for drivers involved in two-vehicle collisions. With one exception (see below), using this new criterion variable does not change the interpretation or (in)significance of the variables analysed in the preceding section. However, almost all estimated odds ratios are closer to 1. This reduction in the estimated effects of the independent variables is not surprising because in combining hospitalized drivers with fatally injured drivers in the outcome variable, we introduce more heterogeneity in the characteristics of the group of drivers with the outcome. Therefore, the characteristics of the drivers who died or are hospitalized after being involved in a two-vehicle collision reported by police are less different than the characteristics of the drivers who were not injured or suffered a minor injury. Hence, the two groups formed by the criterion variable being less different on all other characteristics, it is expected to obtain odds ratios closer to 1. However, the observed differences remain statistically significant.

Using a similar criterion variable as Toy and Hammitt (2003), we can compare some of our results with those of that study. Recall that they used an AIS score greater or equal to 3 to measure the risk of death or serious injury. Here we compare our model given in the third column of Table 3 with their Model 5 in Table 2 (p. 646). Note that the control variables are similar but not exactly the same in these two models. In their study, Toy and Hammitt (2003) found that only pickup trucks were significantly more protective and aggressive than cars. Our own conclusion is that all three types of LTVs are significantly more protective and aggressive than passenger cars. We might tend to assume that the results are divergent, but this is probably not the case, since our odds ratios are all, with one exception (pickup self-protection), within the 95% confi-

Table 4
Results of logistic regression when collisions with property damage only (PDO) are removed

N = 476,013	% of PDO collisions removed in the category	Odds ratios (95% confidence intervals)	
		Risk of death	Risk of hospitalization or death
Driver's vehicle type			
Car	83	Ref	Ref
Pickup	86	**0.73 (0.65–0.81)**	**0.86 (0.83–0.90)**
Minivan	85	**0.68 (0.58–0.79)**	**0.83 (0.79–0.88)**
SUV	86	**0.71 (0.57–0.89)**	**0.90 (0.84–0.97)**
Heavy truck	91	**0.15 (0.11–0.20)**	**0.28 (0.25–0.31)**
Bus	91	**0.14 (0.05–0.38)**	**0.23 (0.17–0.32)**
Type of other vehicle			
Car	84	Ref	Ref
Pickup	84	**2.88 (2.60–3.19)**	**1.73 (1.67–1.80)**
Minivan	84	**1.88 (1.63–2.16)**	**1.27 (1.21–1.34)**
SUV	85	**2.21 (1.85–2.64)**	**1.34 (1.25–1.43)**
Heavy truck	84	**4.61 (3.03–7.01)**	**2.29 (1.87–2.80)**
Bus	86	**4.35 (1.64–11.5)**	1.30 (0.77–2.20)
Mass ratio			
Less than 0.50	82	**2.00 (1.45–2.74)**	**1.63 (1.43–1.86)**
0.50–0.80	82	**1.53 (1.33–1.77)**	**1.18 (1.12–1.24)**
0.80–1.20	83	Ref	Ref
1.20–2.00	85	**0.51 (0.41–0.64)**	**0.72 (0.68–0.77)**
More than 2.00	88	**0.17 (0.04–0.67)**	**0.43 (0.32–0.56)**
Driver's sex			
Female	80	Ref	Ref
Male	86	**1.21 (1.12–1.32)**	**0.93 (0.90–0.96)**
Driver's age			
Under 25	83	**1.01 (0.91–1.12)**	**0.97 (0.94–1.01)**
25–44	84	Ref	Ref
45–64	84	**1.55 (1.41–1.71)**	**1.17 (1.13–1.22)**
65 and +	84	**3.71 (3.34–4.12)**	**1.80 (1.72–1.88)**
Safety belt			
No belt	42	**7.15 (6.48–7.90)**	**4.16 (3.96–4.37)**
Safety belt	51	Ref	Ref
Authorized speed			
Less than 50 kph	83	**0.39 (0.20–0.75)**	**0.64 (0.56–0.73)**
50–60 kph	72	Ref	Ref
70–80 kph	65	**6.22 (5.47–7.08)**	**2.85 (2.74–2.97)**
90 kph	32	**10.41 (9.1–11.9)**	**4.45 (4.24–4.67)**
100 kph	67	**10.00 (8.5–11.7)**	**2.91 (2.74–3.11)**
Collision			
Rear-end	82	**0.15 (0.12–0.17)**	**0.31 (0.29–0.32)**
Side-swipe (same dir.)	95	**0.49 (0.39–0.61)**	**0.50 (0.45–0.54)**
Left turn conflict (same dir.)	89	**0.34 (0.25–0.47)**	**0.78 (0.71–0.85)**
Right turn conflict (same dir.)	94	**0.20 (0.11–0.36)**	**0.57 (0.49–0.66)**
Head-on	78	**5.29 (4.79–5.85)**	**3.02 (2.90–3.15)**
Left turn conflict (diff. dir.)	83	**0.60 (0.52–0.69)**	**0.75 (0.72–0.79)**
Right turn conflict (diff. dir.)	90	1.04 (0.60–1.80)	1.09 (0.90–1.33)
Right-angle (side undetermined)	81	Ref	Ref
Right-angle (driver side impact)	78	**2.16 (1.81–2.56)**	**1.48 (1.39–1.59)**
Other	91	1.14 (0.85–1.54)	**0.87 (0.81–0.93)**

dence intervals computed in their study. Plausibly, this discrepancy in the two studies stems from the fact that our sample size was larger than theirs. This advantage allowed us to obtain shorter confidence intervals and thus more odds ratios that differ significantly from 1. Another possible explanation for this discrepancy is that the potential bias induced by the underreporting of lower severity outcomes can differ between these two studies (Elvik and Mysen, 1999). However, we will see at the end of this section that the estimation of these odds ratio appears to be robust to this potential bias.

It is important to state that, although our sample is large, our main parameters are not only statistically significant, but concretely so: our significant odds ratio closest to 1 is 0.86 (pickup self-protection), a difference of 14% that strikes us as significant in practice.

Comparing the effect of sex in the models shown in Table 3, we see that males are 23% more likely to die than women. Nonetheless, males are 10% less likely to be fatally injured or hospitalized in a collision. This reverse result could be explained by the combination of the following observations. First, Evans (2001) showed that for the same physical impact, females have a higher risk of being killed. Hence, given a collision, females are physiologically more likely to die or to be injured than males. Broyles et al. (2003) found that males have a lower risk of being injured in crashes involving four wheel drives (OR = 0.68) and Toy and Hammitt (2003) obtained a similar odds ratio to ours (OR = 0.96, not statistically significant however), confirming the findings of Evans when the outcome analyzed is “fatal or severe injury”. So, the differences noted between men and women assume a combination of behavioral and physiological factors that significantly affect driver injury severity (Ulfarsson and Mannering, 2004). Second, among all traffic fatalities worldwide, 2.3 males are killed for every female (see Evans, 2004). In our database this ratio is very similar, that is 2.6, and the ratio for the combined outcome “death or hospitalization” is much lower at 1.6. Canadian male drivers are in general adopting more risky driving behavior, such as speeding (Transport Canada, 2008) and drinking (Mayhew et al., 2008), so they are more exposed to severe collisions leading to the drivers' death. This is, at least in part, supported by the rate of convictions for excess speed per licensed drivers that is on average 2.5 times higher for males compared to females and 6.5 times higher for drinking and driving (Société de l'assurance automobile du Québec, 2007). Even though we included in the statistical model some variables that control for the severity of the collisions, this adjustment is only partial as it does not take into account exceeding the posted speed limits and other risky driving behaviors prominently observed in male drivers. Hence, the male to female death ratio of 2.6 in our database and the absence of other control variables measuring risky driving behaviors likely explain the reverse odds ratio of 1.23 showing a significantly higher risk of death for male drivers in two-vehicle collisions reported by police.

The odds ratio for the use of safety belt in the third column of Table 3 is 5.21, showing once again its strong effectiveness in preventing death or injuries requiring hospitalization. This odds ratio is lower than the one obtained for the death criterion. The corresponding odds ratio in the study of Toy and Hammitt (2003) is 2.7 with an upper bound for the 95% confidence interval of 5.0. Our estimates of safety belt effectiveness seem therefore a little higher than what is usually reported in the literature. The drivers' safety belt use in our sample is 97% (Table A2), which is much higher than the average Canadian drivers' safety belt use of 92% reported by Transport Canada for the study period. Safety belt use is mandatory in Canada, therefore drivers who survived a collision with no or minor injuries are likely to overreport its use to police officers (Kahane, 2000). Undoubtedly, this is contributing in overestimating the effectiveness of safety belts. Another factor that explains these higher odds ratios for safety belts in our study is the large proportion of collisions with PDO where safety belt use was generally not stated. Furthermore, it is well recognized that drivers who buckled up are on average involved in less severe crashes than drivers who do not use safety belts (Kahane, 2000). Although other crash characteristics are included in the multiple logistic regression models, the adjustment for crash severity in the estimation of safety belt effectiveness is not as accurate as in the double-pair comparison (Evans, 1986). It is however important to stress that including or not safety belt use and other drivers' and crash characteristics in the logistic regression models had, overall, a negligible or a very small impact on the estimated odds ratios for the covariates of interest in this study i.e. driver's vehicle type and mass ratio (these analyses were made but the results are not presented here).

We recall that our database contains collisions reported by police. Since some studies suggest that lower severity outcomes are less likely to be reported by police (Hauer and Hakkert (1988), Elvik and Mysen (1999)), our database cannot be treated as a random sample of all two-vehicle crashes. For example, a meta-analysis conducted by Elvik and Mysen (1999) suggests that on average 25% of PDO collisions are usually reported by police as opposed to 95% of all fatal collisions. As a result, it is possible that the estimation of some or all our odds ratio is biased (Yamamoto et al. (2008)). In order to study the robustness of each estimated odds ratio with respect to this underreporting problem, we re-performed both regressions using only the 476,013 observations where at least one occupant was injured in the two-vehicle collisions (i.e. non-PDO crashes). The results are presented in Table 4. We can see that even when the reporting rate of PDO collisions goes down to 0%, the estimated odds ratio are essentially the same for our main covariates (driver's vehicle type, other vehicle type and mass ratio) as well as the driver's sex and age. These results suggest that these estimated odds ratios are likely to be robust to the underreporting of PDO crashes.

However, some estimated odds associated with the use of a safety belt, the authorized speed and the configuration of the collision are different when PDO collisions are removed. For example, the odds ratio for the use of a safety belt went from 8.96 to 7.15 for the risk of death and from 5.21 to 4.16 for the risk of death or hospitalization. For each category, the proportion of observations coming from PDO collisions is indicated in Table 4. We can see that the estimated odds ratio of a category can change when this proportion differs from the reference category. For these last three control variables presented (safety belt, authorized speed and the configuration of the collision), the estimated odds ratio given in this table should be used if one wishes to compare our results with studies where only non-PDO crashes are considered.

Table 5
Specific comparisons of vehicle incompatibility (n = 1,261,108)

Drive	Impact with	Mass ratio	Odds ratio	95% Interval
Pickup	Pickup	Smaller	**2.04**	**(1.79–2.34)**
Car	Pickup	Smaller	**1.84**	**(1.71–1.97)**
Pickup	Pickup	=	**1.60**	**(1.41–1.80)**
SUV	Pickup	Smaller	**1.55**	**(1.35–1.78)**
Minivan	Pickup	Smaller	**1.53**	**(1.37–1.71)**
Car	SUV	Smaller	**1.46**	**(1.32–1.62)**
Car	Pickup	=	**1.43**	**(1.34–1.53)**
Car	Minivan	Smaller	**1.40**	**(1.30–1.51)**
Car	Car	Smaller	**1.28**	**(1.22–1.35)**
Pickup	SUV	Smaller	**1.23**	**(1.08–1.41)**
SUV	SUV	Smaller	**1.23**	**(1.05–1.44)**
Minivan	SUV	Smaller	**1.22**	**(1.07–1.39)**
SUV	Pickup	=	**1.21**	**(1.06–1.38)**
Minivan	Pickup	=	**1.20**	**(1.08–1.32)**
Pickup	Minivan	Smaller	**1.18**	**(1.05–1.33)**
SUV	Minivan	Smaller	**1.18**	**(1.02–1.36)**
Minivan	Minivan	Smaller	**1.17**	**(1.04–1.31)**
Car	SUV	=	**1.14**	**(1.03–1.25)**
Pickup	Pickup	Bigger	1.11	(0.97–1.28)
Car	Minivan	=	**1.09**	**(1.02–1.17)**
Pickup	Car	Smaller	1.08	(0.97–1.21)
SUV	Car	Smaller	1.08	(0.94–1.24)
Minivan	Car	Smaller	1.07	(0.96–1.19)
Car	Pickup	Bigger	1.00	(0.91–1.10)
Car	Car	=	1	Ref.
Pickup	SUV	=	0.96	(0.84–1.10)
SUV	SUV	=	0.96	(0.83–1.11)
Minivan	SUV	=	0.95	(0.84–1.08)
Pickup	Minivan	=	0.92	(0.82–1.03)
SUV	Minivan	=	0.92	(0.80–1.05)
Minivan	Minivan	=	0.91	(0.82–1.01)
Pickup	Car	=	**0.84**	**(0.77–0.92)**
SUV	Pickup	Bigger	**0.84**	**(0.73–0.97)**
SUV	Car	=	**0.84**	**(0.75–0.95)**
Minivan	Pickup	Bigger	**0.84**	**(0.75–0.94)**
Minivan	Car	=	**0.84**	**(0.77–0.91)**
Car	SUV	Bigger	**0.80**	**(0.71–0.90)**
Car	Minivan	Bigger	**0.76**	**(0.69–0.84)**
Car	Car	Bigger	**0.70**	**(0.66–0.74)**
Pickup	SUV	Bigger	**0.67**	**(0.58–0.77)**
SUV	SUV	Bigger	**0.67**	**(0.57–0.79)**
Minivan	SUV	Bigger	**0.66**	**(0.58–0.76)**
Pickup	Minivan	Bigger	**0.64**	**(0.57–0.73)**
SUV	Minivan	Bigger	**0.64**	**(0.55–0.74)**
Minivan	Minivan	Bigger	**0.64**	**(0.57–0.72)**
Pickup	Car	Bigger	**0.59**	**(0.53–0.65)**
SUV	Car	Bigger	**0.59**	**(0.52–0.67)**
Minivan	Car	Bigger	**0.58**	**(0.53–0.64)**

4. New representation of vehicle incompatibility

We are now going to represent vehicle incompatibility by looking at essentially all possible combinations of the variables we want to study where the four types of light duty vehicles (passenger car, pickup truck, minivan and SUV) are concerned: the driver's vehicle type, the other vehicle type involved in the collision, and a mass ratio categorization. As our sample is large, each combination of these variables will have enough observations (between 646 and 376,409 observations per category) to attempt a fairly accurate estimate of the associated odds ratio. We now present this new representation and corresponding estimated odds ratios from the logistic regression model.

Table 5 shows, in decreasing order, the odds ratios (and 95% confidence intervals) of the risk of hospitalization or death for 48 types of vehicle incompatibility. The total number of 48 combinations reflects our use of four categories to describe the driver's vehicle type (the "drive" column), four categories to describe the other vehicle type (the "impact with" column), and three categories to characterize the mass ratio (the "mass ratio" column). Note that the mass ratio was categorized as follows:

- "**Smaller**": the mass of the driver's vehicle is at least 20% smaller than the mass of the other vehicle (ratio < 0.8).
- " = ": there is a discrepancy of less than 20% between the masses of the two vehicles (0.8 ≤ ratio ≤ 1.2).
- "**Bigger**": the mass of the driver's vehicle is at least 20% greater than the mass of the other vehicle (ratio > 1.2).

Note that all the other control variables were also included in this regression. We also added all significant double or triple interaction terms between the three main effects (the driver's vehicle type, the other vehicle type, and the mass ratio categorization mentioned above). All collisions involving at least one truck or bus or collisions with missing mass ratios were removed. Therefore, the sample size for this vehicle incompatibility analysis was 1,261,108 drivers. Only odds ratios associated with the 48 vehicle incompatibility comparisons are presented in Table 5. The odds ratios for the main effects of driver's vehicle type, type of the other vehicle, mass ratio and for the control variables are similar to those given in the third column of Table 3.

Studying Table 5, we find as follows:

- Most of the odds ratios significantly greater than 1 are associated with collisions where the driver's vehicle had a smaller mass than the other vehicle. Similarly, the odds ratios significantly less than 1 are associated with collisions where the driver's vehicle was heavier than the other vehicle.
- The aggressivity of pickup trucks is clearly established. For any mass ratio category, the most dangerous collisions are always the ones where the other vehicle is a pickup. Indeed, when we look only at the point estimates of odds ratios, we see that the four types of collisions where the other vehicle is a pickup are always the most dangerous collisions. In addition, it is interesting to note that, when passengers cars are involved, the aggressivity of pickup trucks is comparable to the extra protection of having a car at least 20% heavier (OR = 1.00).
- The low aggressivity of passenger cars is also clearly established. For any mass ratio category, the collisions where the other vehicle is a car are generally among the least dangerous collisions for drivers.
- Collisions involving vehicles of the same type are not necessarily less dangerous: for any mass ratio category, the most dangerous collisions are those involving two pickups.
- When not colliding with pickups, pickups are highly protective. For any mass ratio category, pickup drivers are generally less at risk than drivers of other vehicle types.

5. Conclusion

Logistic regression was used to model the risk of death or hospitalization to drivers involved in two-vehicle collisions. The effects of the aggressivity and self-protection of pickup trucks, minivans and SUVs compared to passenger cars are statistically significant. Pickups emerged as more aggressive than SUVs and minivans. Also, the risks are very large when colliding vehicles have a large mass ratio difference; if the relative proportions of heavy vehicles and light vehicles in the fleet are altered, negative effects on road safety might results.

The most significant contribution of this paper is the use of a very large sample size to study and estimate the effect of vehicle incompatibility. This allowed to directly contrasting specific vehicle types and mass ratios in two-vehicle collisions (see Table 5).

Regarding the control variables, the effects obtained were appreciably similar as those in the literature. However, we note that the risk incurred by males compared to females depends on the dependent variable being modelled. Our results showed that men are more likely to die than women but run less risk of being hospitalized. As mentioned in Section 3.2.2, this reverse finding could be explained by the imperfect control variables used to adjust for the severity of the collision when modelling the risk of death. This study re-iterates that safety belt use is highly effective in reducing injuries and deaths. However, its real effectiveness is most likely lower than our estimated odds ratios due in part to the overreporting of safety belt use by surviving occupants in police reports.

This study is limited in some respects. For one thing, using data from police reports is imprecise because reports tend to overstate the injury severity. The study was limited in its analysis of available information that does not necessarily give an accurate picture of factors contributing to collisions. For example, the information in the database does not tell us which vehicle impacted or was impacted and what the severity of the collision really was. Seatbelt use is missing for almost all collisions with property damage only reported by police and its use is overreported by drivers with no or minor injuries so that the estimation of the seatbelt effect might be biased. Other information that could affect the seatbelt effect and driver status is the presence of airbags and their deployment. This information is currently not routinely reported by police officers. However, we have shown that these factors have a small or negligible impact on the estimated effects of LTVs in terms of both aggressivity and self-protection in two-vehicle collisions. Finally, collisions with property damage only are under reported by police, so the relative frequency of death and of other injury severity categories cannot be used to get unbiased estimates of the incidence of injury severity of drivers involved in two-vehicle collisions.

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Appendix A

Tables A1–A3 show the conditional distributions that reflect the different categories of the independent variables.

Table A1
Relationship between vehicle characteristics and injury severity

	Injury severity (%)				
	None (%)	Minor (%)	Major (hospitalization) (%)	Fatal (%)	% of total (n = 2,999,395)
Driver's vehicle					
Car	87.16	11.97	0.75	0.12	67.30
Pickup truck	92.53	6.71	0.63	0.13	13.83
Minivan	90.19	9.22	0.53	0.07	9.33
SUV	91.04	8.36	0.53	0.07	4.64
Heavy truck	97.45	2.24	0.26	0.04	4.07
Bus	96.90	2.93	0.14	0.02	0.83
Other vehicle					
Car	89.39	10.02	0.53	0.05	67.49
Pickup truck	87.85	11.02	0.95	0.18	13.69
Minivan	87.93	11.29	0.68	0.10	9.32
SUV	89.06	10.18	0.65	0.11	4.63
Heavy truck	85.73	11.44	1.99	0.85	4.04
Bus	88.44	10.50	0.84	0.22	0.82
Mass ratio[a]					
(0.00; 0.50]	84.44	13.55	1.59	0.41	0.84
(0.50; 0.80]	85.70	13.28	0.88	0.14	9.48
(0.80; 1.20]	87.97	11.29	0.67	0.07	20.59
(1.20; 2.00]	91.34	8.20	0.43	0.03	10.95
(2.00; +∞)	96.15	3.64	0.20	0.01	0.80
Not stated	89.19	9.99	0.69	0.13	57.32

[a] Driver's vehicle mass over the other vehicle mass.

Table A2
Relationship between driver characteristics and injury severity

	Injury severity (%)				
	None (%)	Minor (%)	Major (hospitalization) (%)	Fatal (%)	% of total (n = 2,999,395)
Sex					
Female	84.19	14.90	0.82	0.09	33.43
Male	91.01	8.25	0.62	0.12	64.60
Not stated	99.66	0.33	0.01	0.00	1.97
Age					
24 or less	89.00	10.20	0.70	0.10	21.25
25–44	88.31	10.97	0.64	0.08	44.77
45–64	88.55	10.65	0.69	0.12	23.40
65 or +	88.71	9.96	1.03	0.30	7.69
Not stated	99.29	0.67	0.03	0.01	2.90
Safety belt					
Safety belt not worn	56.18	33.42	7.71	2.69	0.88
Safety belt worn	63.06	34.74	1.94	0.26	28.91
Not stated	98.99	0.88	0.11	0.02	70.21

Table A3
Relationship between collision characteristics and injury severity

	Injury severity (%)				
	None (%)	Minor (%)	Major (hospitalization) (%)	Fatal (%)	% of total (n = 2,999,395)
Maximum authorized speed					
Less than 50 kph	88.13	11.48	0.38	0.02	2.05
50–60 kph	78.20	20.99	0.77	0.05	29.21
70–80 kph	70.22	26.09	3.06	0.63	4.82
90 kph	45.51	42.32	9.46	2.71	1.18
100 kph	73.41	23.76	2.13	0.70	2.04
Not stated	95.65	4.00	0.31	0.05	60.70
Configuration of collision					
Head-on	82.49	12.89	3.44	1.18	4.59
Rear-end	88.20	11.47	0.31	0.02	33.74
Side-swipe (same direction)	95.81	3.96	0.19	0.04	8.82
Left turn conflict (same direction)	93.21	6.11	0.63	0.05	2.99
Right turn conflict (same direction)	96.20	3.50	0.29	0.02	2.12
Left turn conflict (diff. direction)	86.94	12.39	0.63	0.05	18.64
Right turn conflict (diff. direction)	93.45	5.80	0.67	0.09	0.52
Right-angle (side undetermined)	86.37	12.56	0.96	0.12	18.52
Right-angle (driver side impact)	85.87	12.33	1.51	0.29	2.06
Other	93.99	5.44	0.50	0.07	2.23
Not stated	94.25	5.18	0.50	0.06	5.76

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