THE EFFECTS OF AUTOMATIC EMERGENCY BRAKING ON FATAL AND SERIOUS INJURIES

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ABSTRACT

The introduction of automatic emergency braking changes the distribution of impact severity thus the resulting injury risk. In the calculation of the possible safety impact, risk functions must be used. These functions can be derived in different ways. In this paper, matched pair techniques have been used to study if the power models developed by Nilsson can be used.

By applying the risk functions on theoretical changes of impact speed as a result of pre impact braking, the possible effectiveness on fatal and serious injuries can be estimated. It was found, that such braking can offer major benefits. A reduction of speed before impact with 10 % can reduce fatal injuries in car crashes with approximately 30 %.

INTRODUCTION

It is well known that speed and change of velocity in crashes are highly related to risk of injury and the severity of injuries (Elvik et al 2004). While the risk of being involved in a crash is only marginally increased for increased speed, injuries and especially serious to fatal injuries are dramatically related to even small changes in travel speed or change of velocity in a crash.

The relation between speed and injury has been demonstrated empirically, theoretically as well as mechanically and on all levels such as at the macro level, in individual crashes as well as on the micro level for biological tissue (Elvik et al 2004). While this is nothing new or controversial, there are still doubts about how risk functions at micro and macro level should be developed and understood. While it is clear, that changes in average travel speed have a major impact on especially serious and fatal injuries, it is also clear, that it is not travel speed in itself that is injurious but rather rapid energy transients in crashes. It can even be questioned if the change of velocity is the best predictor for the risk of injury when in fact mean and peak acceleration is more relevant, although change of velocity and acceleration are of the correlated but not necessarily causally related (Kullgren 1998).

In the traffic safety literature and in practice, the power models are used to describe the relationship between travel speed on a macro level and risk of injury. The power model was firstly applied by Nilsson (2004) in the early 1970s and has since then been validated and evaluated several times. The function, or rather functions, has been revised several times, but in essence the proposed functions have been close to each other.

In the biomechanical and injury epidemiological literature, the relationship between impact severity, i e change of velocity, and injury has been described as dose response functions with increasing slope (Evans 1986). Both power as well as other continuously increasing functions has been applied to injury data (Krafft 2000a and b). There are many examples for both car occupants as well as pedestrians and also in different crash configurations and trajectories (Elvik et al 2004).

Crash protection for cars has been increased radically over the past 10 years or so, and to such extent that it can be not only demonstrated in simulated impact tests, but also in epidemiological studies (Lie and Tingvall 2002). It has also been demonstrated many times that the mass relation between cars in two car crashes is correlated to injury risk and severity (Krafft 2000a and b). In both examples, speed and change of velocity are critical factors. While in the former example, the consequence of improved safety is that the car can be crashed at a higher speed with the same injury outcome, or rather that for a given speed or speed distribution, the risk of injury and the severity of injury has been reduced. This factor can possibly

be measured in speed capability i e that the improvement can be expressed in terms of speed.
In the latter case, it is obvious that the change of velocity can vary greatly with mass relations in two car crashes and that this is important for injury outcome. In both cases, though, it has been observed, that fatal and serious injuries are more affected by speed and change of velocity, than minor injuries (Nilsson 2004, Elvik et al 2004). This is much in line of the implication of the power model for the overall relationship between travel speed and injury risk.

While the link between travel speed and impact speed is not fully understood, it seems logical that there is some kind of relationship, and therefore it is of interest to study if the power model for travel speed could be used also for car safety and the relation between impact speed and injury outcome.

More recently, cars have been developed and introduced with autonomous automatic emergency braking. Such systems can react to a car in the same direction, to fixed objects and to pedestrians, but are also likely to be expanded to oncoming vehicles and even vehicles in oblique direction. In some situations crashes can be avoided, in other situations crashes can be less severe, mitigated, by braking before impact. Some systems can use almost full braking power, and brake almost 2 seconds before impact. In doing so, speed before impact can be reduced by maybe up to 35 km/h or even more in some situations. This is a substantial change of impact severity.

In order to calculate the potential effects of automatic emergency braking, it is essential to use a solid link between velocity and injury.

The aim of the present study was to;

- With empirical data evaluate if variations in change of velocity in a crash and the resulting outcome can be described by the power model.
- Estimate the importance of automatic emergency braking

THE POWER MODEL

In simple terms the power model is a concept containing a set of power functions for crashes, minor injuries, serious injuries and fatal injuries. The functions are describing relative changes and can normally not give a direct link to absolute travel speed or absolute change of velocity in a crash.
Below are the functions as presented by Nilsson (2004).
Number of fatal crashes:
$Y_1 = (V_{1/} V_0)$^4 * Y_0

Number of fatalities:
$Z_1 = (V_{1/} V_0)$^4 * $Y_0 + (V_{1/} V_0)$^8 * $(Z_0 - Y_0)$

Number of serious crashes:
$Y_1 = (V_{1/} V_0)$^3 * Y_0

Number of serious injured:
$Z_1 = (V_{1/} V_0)$^3 * $Y_0 + (V_{1/} V_0)$^6 * $(Z_0 - Y_0)$

Number of slight crashes:
$Y_1 = (V_{1/} V_0)$^2 * Y_0

Number of slightly injured:
$Z_1 = (V_{1/} V_0)$^2 * $Y_0 + (V_{1/} V_0)$^4 * $(Z_0 - Y_0)$

The following estimates based on a meta analysis, were proposed by Elvik et al (2004), to be used. They were validated against minor to moderate changes in travel speed. The differences between crash outcome and outcome for an individual should be noted. In the present study, the result of the meta analysis has been used.

Crash or injury severity	Exponent	Interval
Fatalities	4.5	4.1-4.9
Seriously injured	3.0	2.2-3.6
Slightly injured	1.5	1.0-2.0
All injuries	2.7	0.9-4.5
Fatal crashes	3.6	2.4-4.8
Serious injury crashes	2.4	1.1-3.7
Slight injury crashes	1.2	0.1-2.3
All injury crashes	2.0	1.3-2.7
Property damage only crashes	1.0	0.2-1.8

One major issue in using the power models for either crashes or their outcome, or using it for crash outcome given that a crash has occurred would be that the power for a fatality, serious injury or minor injury would be reduced by 1. That would mean that for fatalities the power is 3.5, for serious injuries 2 and for minor injuries 0.5. This is well in line with that the probability of a crash only is just linear. It is however important to keep this property of the power models in mind when studying either travel speed and outcome or crash protection given that a crash occurs. It would also be important to keep this in mind when looking at different technologies and the distinction of for example emergency braking where the full power levels would be used, or improved occupant protection through improved restraints or structure where the reduction of power would be applied. In table 1, the impact of changes in speed on injuries of varying severity can be seen. An increase of 10% on speed can be seen to increase minor injuries with 15%, serious with 33% and fatal injuries with 53%. The differences in the impact of speed change become even larger with larger increase or decrease of speed.

Table 1.
The influence of changing speed on the increase or decrease of the relative number of minor, serious and fatal injuries with power 1.5, 3.0 and 4.5

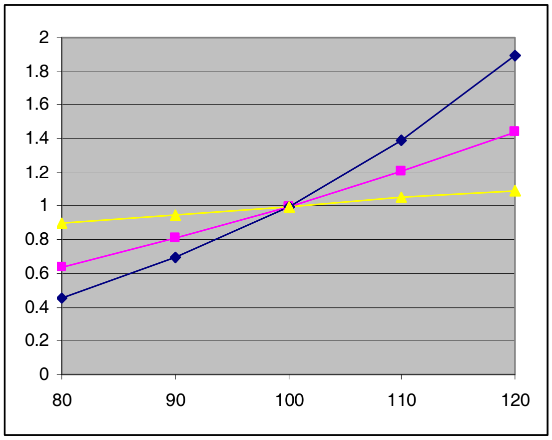
Speed, index	Minor injuries	Serious injuries	Fatal injuries
80	0,72	0,51	0,37
90	0,85	0,73	0,62
100	1	1	1
110	1,15	1,33	1,53
120	1,31	1,73	2,27

In table 2, the lower power levels have been applied, as in the case where only the outcome given a crash is considered. It can be seen that especially for minor injuries, the impact of speed becomes limited while for fatal injuries, the impact is still substantial. The figures can also be seen in figure 1.

Table 2.
The influence of changing speed on the increase or decrease of the relative number of minor, serious and fatal injuries with power 0.5, 2.0 and 3.5

Speed, index	Minor injuries	Serious injuries	Fatal injuries
80	0,89	0,64	0,46
90	0,95	0,81	0,69
100	1	1	1
110	1,05	1,21	1,40
120	1,09	1,44	1,89

Figure 1.
Risk functions for minor, serious and fatal injuries with power 0.5, 2.0 and 3.5 relative to speed index



Risk calculations in the present study were based on matched pair technique. The validation of the power model was in most cases based on the relation between fatal, serious and minor injury. In the first analysis of the relative importance of improved crash protection of newer cars, the relative risk was calculated in two car crashes where the case car population was matched with the average crash population.

In the second analysis, the opposite cars were varied with mass, so that the relative importance of increased and decreased change of velocity could be calculated. This is done under the assumption that relative impact velocity is the same across all masses within the mass range 900 to 1500 kg.

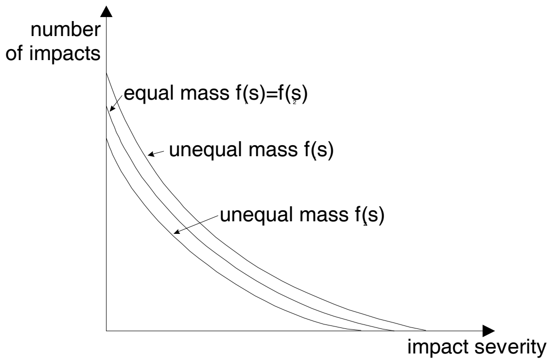
METHOD

Basically, the change of velocity can be calculated from the law of the conservation of momentum;
Delta v = $V_{rel} (M_2 / M_1 + M_2)$,

V_{rel} is the relative velocity and M_1 and M_2 the masses of the two vehicles colliding.
This relation is true even if the two vehicles involved do not have a common velocity after the impact. If the masses are equal, both vehicles will undergo the same change of velocity. This method uses this fact, and that any deviation in mass can be transferred to differences in change of velocity, as long as the individual masses are known (Figure 2). The method cannot generate absolute figures, only risks relative to each other.

Instead of generating new risk functions, the method uses the change on the exposure distributions and the resulting change in risk.

Figure 2.
Impact severity (delta-V) for cars in matching crashes for equal mass: $f_1(s) = f_2(s)$ and unequal mass: $f_1(s) \neq f_2(s)$ where car 1 is of less mass than car 2



The basis for the statistical method is the paired comparison technique, where two car accidents are used to create relative risks. The method was initially developed by Evans (1986), but has been developed further for car to car collisions by Hägg et. al. (1992). The assumption for the method is that the risk of injury is a continuous function of change of velocity. This assumption might conflict with safety features such as airbags that might generate a step-function. This would have to be further investigated. Another assumption is that injuries in one car are independent from the injuries in the other car, given a certain accident severity.
For a given change of velocity the risk of an injury is p_1 and p_2 in the two cars, respectively. For that change of velocity, the outcome of the accident is described in table 3. The outcome of summing over all change of velocities is described in table 4.

Table 3.

Probabilities of injury to driver in car 1 and 2 in a segment of impact severity

		Driver of Car 2		
		driver injured	driver not injured	Total
Driver of Car 1	driver injured	$n_i P_{1i} P_{2i}$	$n_i P_{1i} (1-P_{2i})$	$n_i P_{1i} P_{2i} + n_i P_{1i} (1-P_{2i}) = n_i P_{1i}$
	driver not injured	$n_i (1-P_{1i}) P_{2i}$	$n_i (1-P_{1i}) (1-P_{2i})$	
	Total	$n_i P_{1i} P_{2i} + n_i (1-P_{1i}) P_{2i} = n_i P_{2i}$		

Table 4.

Sums of probabilities of injury to driver in car 1 and 2 in a segment of impact severity

		Driver of Car 2		Total
		driver injured	driver not injured	
Driver of Car 1	driver injured	$\sum_{i=1}^{m} n_i P_{1i} P_{2i} = x_1$	$\sum_{i=1}^{m} n_i P_{1i} (1-P_{2i}) = x_2$	$\sum_{i=1}^{m} n_i P_{1i} P_{2i} + n_i P_{1i} (1-P_{2i}) = n P_1$
	driver not injured	$\sum_{i=1}^{m} n_i (1-P_{1i}) P_{2i} = x_3$	$\sum_{i=1}^{m} n_i (1-P_{1i}) (1-P_{2i}) = x_4$	
	Total	$\sum_{i=1}^{m} n_i P_{1i} P_{2i} + n_i (1-P_{1i}) P_{2i} = n P_2$		

The relative risk of an injury, for vehicle 1 to 2, given a certain change of velocity distribution is therefore:

$$R = (x_1 + x_2) / (x_1 + x_3) = \frac{\sum n_i P_{1i}}{\sum n_i P_{2i}} =$$

$$\frac{\sum n_i P_{1i} P_{2i} + \sum n_i P_{1i} (1 - P_{2i})}{\sum n_i P_{1i} P_{2i} + \sum n_i (1 - P_{1i}) P_{2i}}$$

The method is unbiased for any combination where the vehicles are of the same weight; i.e. the mass ratio is 1. If the vehicles are of different weights, the two vehicles will undergo different changes of velocity, which will have to be compensated for. Generally, we can introduce any component, K that will affect the risk of injury in either, or both of the vehicles. If we let K_1 denote this factor in vehicle 1, and K_2 in vehicle 2, this will lead to:

(1) $n_i P_{1i} P_{2i} K_1 K_2 / n_i P_{2i} K_2 + \dots + n_i P_{1i} P_{2i} K_1 K_2 / n_i P_{2i} K_2 = \sum_{i=1}^{m} n_i P_{1i} P_{2i} K_1 / \sum_{i=1}^{m} n_i P_{2i}$

$$= K_1 \sum_{i=1}^{m} n_i P_{1i} P_{2i} / \sum_{i=1}^{m} n_i P_{2i}$$

To solve the equation, cars of different weights will be used, where the weights are known. K will therefore denote the role of change of velocity, and could be a constant, or a function of, say, change of velocity.

(1) is estimated by $K_1 (X_1 / (X_1 + X_3))$ (2) and, $K_1 = \dfrac{(X_1/(X_1+X_3))_{m_b}}{(X_1/(X_1+X_3))_{m_a}}$ (3) where,

m_a and m_b are mass relations in the matched pairs. These mass relations are transformed to relative change of velocity by

$$\frac{m_b}{m_a} = \left(m_2/(m_1+m_2)\right)_b / \left(m_2/(m_1+m_2)\right)_a$$

The analytical functions chosen to describe the risk functions have been applied simply using either a linear function or a power function. This issue would have to be further investigated using more advanced material.

It is obvious, that while the importance of a marginal change of velocity will be calculated, as well as parts of the risk function, absolute values cannot be given. If this is to be done, a key value must be brought into the equation.

MATERIAL

Police reported data containing at least one injured person on two car crashes in Sweden year 1996-2006 was used for the analysis. While police reported crash data is known to suffer from a number of quality problems, none of them is likely to influence the findings of this study to any large degree.

RESULTS

Two analyses were conducted. In the first, cars of different year models were compared, one set of vehicles from year model 1988 to 1990 and one set from year model 1998 to 2000, in order to study if both older and newer car crash protection could be described by the power model. In table 3, the risk ratios with matched pairs could be seen. While the result cannot be fully explained by improved safety but also increase in weight, it is obvious that the risks have decreased dramatically for fatalities and much for serious injuries while minor injuries have only been affected slightly.

Table 5.
Relative risk of minor, serious and fatal injury for cars of different year models and equivalent speed reduction

	1988-1990 Relative risk	1998-2000 Relative risk	Injury reduction %	Speed equivalent %
Minor injuries	1.02	0.99	- 3	- 6
Serious injuries	1.18	0.86	- 27	- 14
Fatal injuries	1.35	0.81	- 40	- 14

It can be seen in table 5, that the resulting speed reduction is similar for the three injury severity levels. The equivalent speed reduction for minor injuries is slightly lower, but if a 14% speed reduction would be applied, the reduction in injury risk would have to be 7% instead of 3%, which is a small difference.

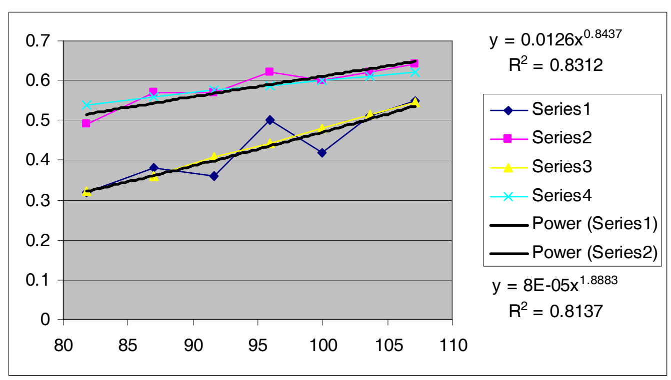
In the second analysis, the importance of change of velocity is demonstrated. By varying the weight of the opponent vehicle, the change of velocity component could be studied in isolation. This can be seen for minor and serious injuries.

Table 6.
Expected and real outcome

Weight kg	Rel Delta V	Expec. SI	Expec. MI	Outcome SI	Outcome MI
900	81.8	0.32	0.54	0.32	0.49
1000	87.0	0.36	0.56	0.38	0.57
1100	91.7	0.41	0.58	0.36	0.57
1200	96.0	0.44	0.59	0.50	0.62
1300	100	0.48	0.60	0.42	0.60
1400	103.7	0.52	0.61	0.51	0.62
1500	107.1	0.55	0.62	0.55	0.64

In figure 3, the data from table 6 has been used to generate regression functions for the real life outcome of relative risks for increasing weight of the opposite car, i e higher change of velocity. The function reinforce that the best representation of a power function of more or less the same order as predicted by the power model. For minor injuries, the power is 0.84 instead of 0.5, and for serious injuries 1.89 instead of 2. Fatal injuries could not be calculated because of small numbers.

Figure 3.
The relation between relative change of velocity (x-axis), real outcome of serious and minor injuries (series 1 and 2), predicted outcome for serious and minor injury (series 3 and 4) and regression lines and functions



In order to control for all severity types, including fatalities, a double pair match with the relative risks between two vehicles was conducted. It was estimated through the power functions that the relative risk would vary with the weight for both vehicles, so that for serious injuries, the risk for increasing weight would be doubled, and contrary for the opposing vehicle. The opposite vehicle would always be the average car with an average weight of 1300 kg.

Figure 4.
Calculated (series 1) and actual (series 2) matched pair risks for cars of different weights, minor injuries. Relative speed refers to case car

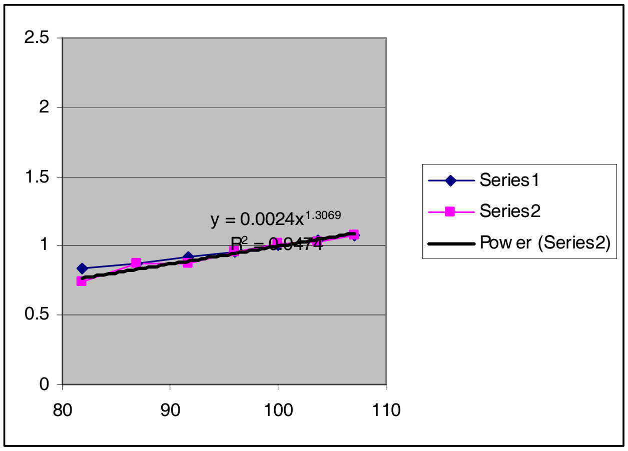


Figure 5.
Calculated (series 1) and actual (series 2) matched pair risks for cars of different weights, serious injuries. Relative speed refers to case car

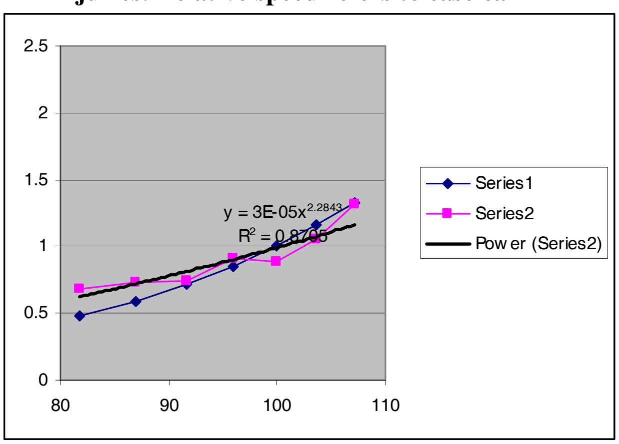
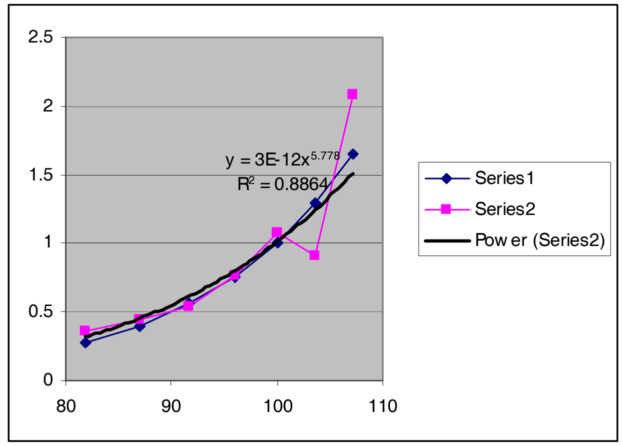


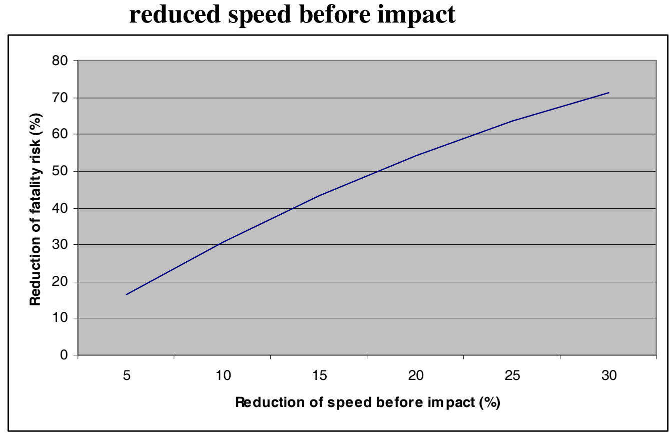
Figure 6.
Calculated (series 1) and actual (series 2) matched pair risks for cars of different weights, fatal injuries. Relative speed refers to case car



Figures 4 to 6 shows that the relationship between speed via relative change of velocity is almost totally in line from what could be expected from the power models. Even for fatalities, with the extreme power of changing speed, expected and real life outcome are very close. In that sense, there is not much to be explained by any added risk reduction from improves safety from more heavy cars, most of the variation could be explained simply by varying change of velocity.

The potential effects of automatic emergency braking can be calculated using the power model. While in case of braking before impact, both the energy level as well as change of velocity will be altered. Using the power model for the calculation of the effects can only pick up the change of velocity. Simply used, a reduction of speed before impact by, say, 10 %, gives a reduction of fatality risk by 31 % and the risk of a serious injury by 19 %.

Figure 7.
The reduction of fatality risk (%) in relation to reduced speed before impact



DISCUSSION

The relation between speed, speed reduction and the risk of injury of different severities is well known and generally established (Elvik et al 2004). The underlying theory is less well known and explained, but the fact that the more serious injury, the more sensitive to change of velocity seems to be found in many different kinds of studies (Kullgren 2008)

The idea that car safety can be described, at macro level, in speed and speed reduction seems natural but has only been used in looking at change of velocity studies. In this study, it is demonstrated that speed and change of velocity play a major role in explaining variations on safety. Furthermore, is has been demonstrated that the power model, implying that the impact of speed would vary with injury severity, is valid. The finding, that the power models are valid, is not in itself surprising, but has a number of implications, where one is demonstrated in this study.

The results can be used to demonstrate the impact of active or integrated safety systems like brake assist (EBA) or autonomous emergency braking and for validation of the safety impact of such systems. It can be expected that emergency braking, if reducing the speed before an impact with, say 10 %, can reduce the risk of a fatal injury with approximately 30%. This would be expected in crashes into fixed objects, while the reduction would be different in a car to car frontal collision where occupants in both vehicles would benefit. The total effect in a frontal impact would though not be lower, in fact the likely outcome is an even greater effect. Based on analysis of data from crash recorders Kullgren (2008) estimated a reduction of AIS2+ injuries in frontal crashes of more than 40% if the impact speed could be reduced with 20 km/h in all cashes. The studies show a major if not dramatic consequence of new technology and probably more than what is expected intuitively.

The method used could only pick up the consequences of reducing speed before impact on the change of velocity. The crash energy would also be reduced thus limiting the risk of intrusion, which also influence injury risk. The expected benefits of braking are therefore likely to be larger than presented here.

There are other methods to generate risk functions, such as crash recorders (Kullgren 1998, Kullgren 2008). Such methods have the potential to also increase the knowledge about distributions of absolute impact velocities or at least distribution of change of velocity. In doing so, the effects of braking could be further estimated.

Braking before impact could also avoid crashes, which would imply that the power should be raised by one unit, leaving us with even higher effects. This could be the case for pedestrian impacts. If the power 4.5 would be used, a 10 % reduction of speed before impact would lead to a 40 % reduction of fatalities. The data in this study can though not be used to validate the risk functions for pedestrian impacts, and whether the power model is applicable for pedestrians.

Finally, the study once more demonstrate the general impact of speed, and that speed is more related to the outcome of a crash rather than the incidence of a crash. While this might not be how citizens perceive the role of speed, the introduction of automatic emergency braking implies that such knowledge should be brought to the general public to increase the demand for automatic braking systems.

CONCLUSIONS

- By using empirical data, it seems that the power models are applicable to estimate the role of change of velocity on fatal and serious injury
- By using the power models, it can be estimated that automatic emergency braking can have a major effect on fatal and serious injury. A 10 % reduction of speed before impact can lead to 30 % reduction of fatality risk and 19 % on the risk of a serious injury

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