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Intelligent Speed Adaptation (ISA): benefit analysis using EDR data from real world crashes

SD Doecke, SJ Raftery, ME Elsegood, JRR Mackenzie

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AUTHORS

SD Doecke, SJ Raftery, ME Elsegood, JRR Mackenzie

PERFORMING ORGANISATION

Centre for Automotive Safety Research
The University of Adelaide
South Australia 5005
AUSTRALIA

SPONSORED BY

Transport Accident Commission
PO Box 742
Geelong, Victoria 3220
AUSTRALIA

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ABSTRACT

Intelligent Speed Adaptation (ISA), sometimes also referred to as Intelligent Speed Assist, is a technology that is designed to reduce the amount of time vehicles are driven above the speed limit and reduce the degree to which the speed limit is exceeded. ISA has three forms; limiting, supportive and advisory ISA. Previous studies have calculated a reduction in crashes by focussing on changes in speed profiles and the influence of travel speed on risk of injury. The aim of this study was to determine how ISA would directly affect the severity of a crash using information from event data recorder (EDRs). This study also included a literature review focused on previous ISA trials that examined factors that influence compliance with advisory and supportive ISA. It was found that ISA can result in substantial reductions in impact speed in a crash, and if all vehicles were fitted with ISA fatal and serious injuries would be reduced by 17.6% with limiting ISA, 8.1 to 12.3% with supportive ISA, and 5.1 to 9% with advisory ISA.

KEYWORDS

Intelligent Speed Adaptation (ISA), Speeding, Injury Severity

Summary

Intelligent Speed Adaptation (ISA), sometimes also referred to as Intelligent Speed Assist, is a technology that is designed to reduce the amount of time vehicles are driven above the speed limit and reduce the degree to which the speed limit is exceeded. ISA was conceptualised in three forms; advisory ISA that simply alerts the driver when they are exceeding the speed limit, supportive ISA that prevents the vehicle from exceeding the speed limit but can be over-ridden by the driver, and limiting ISA that prevents the vehicle from exceeding the speed limit and cannot be overridden. In limiting the amount of speeding and the level of speeding, ISA is expected to reduce the likelihood and severity of crashes.

Previous studies have calculated a reduction in crashes by focussing on changes in speed profiles and the influence of travel speed on risk of injury. The aim of this study was to determine how ISA would directly affect the severity of a crash using information from event data recorder (EDRs).

This study also included a literature review focused on previous ISA trials that examined factors that influence compliance with advisory and supportive ISA. This was conducted to assist with predicting the effect of advisory and supportive ISA. The literature review found that reduced efficacy of ISA has been observed for males, young drivers, and drivers who like or intend to speed. It also found ISA is most likely to be ignored or overridden when drivers are overtaking, running late, and when driving on urban arterial roads.

The data source for the analysis was the CASR-EDR database. This database combines data extracted from the Event Data Recorder (EDR) of crashed vehicles with matched police reports. This process results in accurate knowledge about pre-crash speeds along with the speed limit where the crash occurred such that incidents of speeding can be determined. A model of ISA was developed and applied to the EDR data to calculate a new impact speed. Risk curves were used to determine the resulting change in fatal and serious injury probability.

It was found that ISA can result in substantial reductions in impact speed in a crash, and if all vehicles were fitted with ISA:

- Limiting ISA could reduce serious injuries by 17.6%, or 7,040 per year in Australia.
- Supportive ISA could reduce serious injuries by 8.1 to 12.3%, or 3,240 to 4,920 per year.
- Advisory ISA could reduce serious injuries by 5.1 to 9%, or 2,040 to 3,600 per year

Supportive ISA systems appear to be the best ISA type for regulation, having shown strong user acceptance in other studies, and moderate safety benefits in this study and previous studies.

Limiting ISA should be mandated for repeat speed offenders once technical limitations have been overcome, as these are the drivers that will benefit from ISA the most but are the most likely to ignore an advisory or supportive system that can be over-ridden.

Contents

1 Introduction

Intelligent Speed Adaptation (ISA), sometimes also referred to as Intelligent Speed Assist, is a technology that is designed to reduce the amount of time vehicles are driven above the speed limit and reduce the degree to which the speed limit is exceeded. ISA was conceptualised in three forms; advisory ISA that simply alerts the driver when they are exceeding the speed limit, supportive ISA that prevents the vehicle from exceeding the speed limit but can be over-ridden by the driver, and limiting ISA that prevents the vehicle from exceeding the speed limit and cannot be overridden.

In limiting the amount of speeding and the level of speeding, ISA is expected to reduce the likelihood and severity of crashes. Previous studies have calculated the effect of ISA on crashes using either Elvik's power model (Elvik, Christensen & Amundsen, 2004) or Kloeden's relative risk curve (Kloeden, McLean, Moore & Ponte, 1997; Kloeden, Ponte & McLean, 2001). Elvik's power model has been used to equate changes in mean speed with changes in crash frequency at different injury severities (e.g. Driscoll, Page, Lassarre & Ehrlich, 2007). Kloeden's relative risk curve has been used to predict the difference in casualty crashes for a given change in speed distribution (e.g. Tate & Carsten, 2008; Doecke, Anderson & Woolley, 2010).

These previous studies found that limiting ISA provided the most safety benefit, followed by supportive and advisory (Tate & Carsten, 2008; Doecke, Anderson & Woolley, 2010). However, it is worth noting that more than 10 years after this research advisory ISA is the predominant type of ISA system that is available as original equipment on new vehicles. It is also the only type of ISA that has been included in proposed regulation, the EU's 2022 update to the "regulation on the general safety of motor vehicles and the protection of vehicle occupants and vulnerable road users". It seems likely that this is due to real or perceived consumer demand and/or public acceptance.

Consumers have, over time, come to demand that vehicles provide a certain level of safety, with features such as airbags and crash avoidance technologies becoming selling points. These safety features have a clear link to crashes, either in avoidance or injury mitigation, that can be easily understood by consumers. By contrast, the link between ISA and crashes (avoidance and mitigation) may be less clear to consumers as the link between travel speeds and safety, while well understood by road safety professionals, continues to be met with some scepticism in the general public. It is therefore important to be able to clearly demonstrate how ISA can directly affect the outcome of a crash.

The aim of this study is to determine how ISA would directly affect the severity of a crash. The recent development of the CASR-EDR database presents an opportunity to achieve this aim. Event data recorders (EDRs) record driving data, such as travel speed, impact speed, and brake usage, in the seconds leading up to a crash. The effects of ISA can be applied to this pre-impact data to estimate how ISA could have changed the outcome of the crash. Using EDR data from actual crashes to derive the benefit of ISA would provide an estimated benefit that is based on real-world crash situations, clearly linking ISA to crash avoidance and mitigation.

As advisory ISA simply notifies the driver when they have exceeded the speed limit, the major factor that will determine its effectiveness is who is likely to follow the systems advice and who is likely to simply ignore it. This is also somewhat true of supportive ISA systems, although these need to be actively overridden rather than ignored. To determine the effect of these types of ISA system the likelihood of a driver responding to the advisory notification or accepting the speed limiting support will need to be estimated. To assist with this task this study includes a literature review focused on previous ISA trials that examined factors that influence compliance with advisory and supportive ISA.

2 Literature review

The aim of this literature review is to identify the characteristics of drivers who exceed the speed limit despite the presence of an ISA system in their vehicle; the circumstances of speeding are also considered. Two types of ISA systems were considered: advisory ISA, which provides a warning (visual, auditory, or both) when a driver exceeds the speed limit, and supportive ISA, which prevent vehicles exceeding the speed limit but can be overridden by the driver. The supportive ISA systems included in the research obtained for this review often included the types of warnings provided by advisory ISA systems.

Several studies have demonstrated the positive effect of (most commonly advisory) ISA on vehicle speeds. These studies generally indicated drivers spend significantly lower durations of their trips travelling above the speed limit. When they did exceed the speed limit they returned to the speed limit sooner than when driving without ISA present (e.g., Jamson, 2006; Jiminéz et al., 2008; Regan et al., 2006; Stephan et al., 2014; TfNSW, 2010; van der Pas et al., 2014; Vlassenroot et al., 2007; Warner & Aberg, 2008). From this research it is also evident that ISA can have differential effects on drivers. While, on the whole, studies find ISA to be effective, they also demonstrate that drivers still exceed the speed limit when ISA is operational, and that ISA is less effective for some drivers. These studies tend to follow similar formats when reporting statistical findings and generally report the effect on mean speeds and the proportion of drivers that comply (or do not) with speed limits when ISA is present. While such results can be generalisable to a wider population, there is a need for caution when applying this information to a sample of crashes as this level of information is insufficient to identify individuals most likely to speed. This is illustrated further in the discussion below.

For whom is ISA least likely to be effective?

One of the most interesting findings from the literature is that ISA is generally more effective as the age of the driver increases. Young drivers have been found to spend both more time speeding and more time travelling with an ISA system overridden or switched off (when possible to do so) than older drivers. In an on-road trial of ISA in NSW (TfNSW, 2010), data from 106 vehicles and driver surveys demonstrated that, when an advisory ISA system was operational, 89% of vehicles reduced the amount of time spent speeding and that 24.1% of vehicle travel time was spent speeding (compared to 36.3% before and 30.5% after). This indicates that 11% of vehicles did not reduce the amount of time spent speeding but we are unable to determine which ones, nor is it possible to determine for how long vehicles were speeding when they exceeded the speed limit. Males and females were comparable in the proportion of reduction in speeding time. Young drivers (aged 25 years or younger) were significantly less likely to reduce the proportion of time spent speeding with 77% young drivers reducing their time spent speeding compared to 93% of older drivers.

The NSW trial also included a survey of the drivers involved (TfNSW, 2010). This survey data revealed that 11% of drivers reported turning off the ISA on “a fair proportion of trips” while 47% reported doing so “on the odd occasion”. Further analysis found that 80% of the drivers who regularly turned off ISA were under 25 years old. Provisional licence holders turned ISA off more than fully licensed drivers (31% vs. 5%), and only 13% of provisional drivers never turned the system off compared with 49% of fully licensed drivers. Field trials of ISA undertaken in the UK observed similar patterns during which younger drivers, males, and those with an intention to speed were found to override ISA more often than older drivers, females, and those who did not intend to speed (Lai & Carsten, 2012).

Studies investigating the acceptability of ISA demonstrate that the technology is least acceptable to those for whom it would be most beneficial. Vlasenroot et al. (2011) found that drivers least accepting of ISA included those who like to speed in high-speed zones, drivers aged 25-45, and those who were considered “frequent speeders”. In a small sample of drivers (N=18) involved in ISA trials in simulator and on-road trials, Jamson (2006) also found that drivers who were more likely to speed were less accepting of ISA. Given such findings, there is the possibility that ISA could be less effective for drivers with a history of speeding offences.

Two studies have investigated the use of ISA with recidivist speeding offenders: the Repeat Speeders Trial in Victoria, Australia (Stephan et al., 2014; Young et al., 2013) and the Dutch Speedlock trial in the Netherlands (van der Pas et al., 2014). The Victorian trial assessed the benefits of an advisory system while the Dutch trial examined both advisory and supportive systems. Both studies demonstrated ISA systems reduced the time drivers spent over the speed limit. The Victorian trial also found the drivers with ISA returned to the speed limit faster than the control group who did not have ISA. Young et al. (2013) reported that ISA was particularly effective for drivers aged 50 or older and for those identified as having a propensity for “angry driving”. The Victorian trial also found no differences in effectiveness between drivers classified as high- or low-level speeders, although it should be noted that very high-risk (drivers defined as drivers who spent 10% of time driving 15 km/h above the speed limit on two or more days per week or exceeded the speed limit by 35 km/h for at least 15 seconds three or more times during a week) were excluded from the trial (Stephan et al., 2014; Young et al., 2013).

The Dutch trial produced similar results but found the Speedlock (supportive) system to have a greater effect than the Speedmonitor (advisory) system. Interestingly, in the Dutch trial, drivers with the Speedlock system were found to have a higher mean speed than those with the Speedmonitor system, likely because those in the latter could drive to the maximum speed to which the limiter was set (which was the speed limit + a margin) whereas those in the latter were required to regulate speed themselves. This suggests monitoring devices may be more effective for speeding offenders (because the mean speeds were lower), but the study also found that the more serious offenders were also more likely to override the system. Each system featured an override switch to disable the system for a short period – this was designed to allow for errors in the speed mapping (e.g. where the speed limit was not correct). Participants using the override switch were required to provide the reason for doing so at the end of each trip for each instance of use (van der Pas et al., 2014).

These findings demonstrate that ISA can have some benefit for repeat speeders. It is worth noting that the offenders included in these studies had been convicted of an offence and were undergoing the trials as a result, which may have increased motivation for compliance with the ISA device. It is not clear how ISA may work with repeat speeders who are not convicted or have ISA installed under the supervision of the relevant authority (e.g. criminal justice system). Unfortunately, both trials found drivers invariably returned to their old speeding habits once ISA was removed (Stephan et al., 2014; van der Pas, 2014).

With evidence that drivers more likely to speed are more likely to override or turn off ISA systems, Stephens et al. (2017) conducted an investigation into the self-reported speed compliance and attitudes of a representative sample of Australian drivers. They found that the proportion of drivers who self-reported complying with the speed limit decreased with increasing speed limits (speed limits in the study included 40, 50, 60, and 100 km/h); 79% reported compliance in 40 km/h zones but this reduced to 53% in 100 km/h zones. Classifying participants based on their level of compliance with speed limits across all zones revealed 44% of the sample were compliant (i.e., did not report speeding in any speed zone), the remaining non-complaint drivers (56% of total sample) were further categorised based on their severity of speeding, identifying: 36% as low-level speeders (≤5 km/h over), 17% as mid-level (≤10 km/h over), and 3% as excessive speeders (≥11 km/h over). Among these, drivers aged under 25 accounted for 20% of mid-level, and 33% of excessive speeders, yet comprised only 17.5% of the total sample. Drivers aged 22-25 were also found to have the lowest level of non-compliance (65%), followed by 26-29 year olds (64%), and those aged 40-59 (52%). In terms of licence types, non-compliance was reported by 25% of learner drivers, 59% for probationary drivers, and 57% for unrestricted drivers.

Interestingly, a large proportion of drivers from each group (compliers and non-compliers) thought ISA could be personally useful (63% of low-level speeders, 56% of mid-level, and 55% of excessive), which may suggest some degree of acceptability not observed in other studies.

Situations in which ISA is least likely to be effective

Further to the characteristics of drivers for whom ISA has reduced effectiveness, some studies have identified situations under which drivers are more likely to ignore warnings or override the ISA. The findings here can be somewhat contradictory so careful consideration is necessary before using these variables for analysis. Jamson (2006) observed that drivers in a simulator study were more likely to intentionally turn off ISA in order to speed in lower speed zones and most likely to have ISA active for high speed zones. However, Lai and Carsten (2012) found drivers in the UK trial override the ISA most commonly on 70 mph (approx. 113 km/h) roads, while the second most common speed zone in which ISA was overridden was 20 mph (approx. 32 km/h). They also found that drivers spent more time driving with ISA overridden on arterial roads. Studies that also examine why ISA has been ignored or overridden have found that the most common reasons appear to be when overtaking another vehicle, when running late, or when feeling pressured to match the (faster) speed of surrounding traffic (Jamson, 2006; Young et al., 2013). There is also some indication that ISA is sometimes unnecessary on urban roads due to congestion restricting speeds (Jamson, 2006).

Summary

In summary, while ISA has been found to be effective for most drivers, reduced efficacy has been observed for:

- males,
- young drivers, and
- those who like speeding or intend to speed.

The circumstances when ISA is least likely to be used has varied between studies, although as a guide it would appear it is most likely overridden:

- when overtaking,
- when running late, and
- when driving on urban arterial roads.

3 Methods

An overview of the process by which the benefits of ISA were determined is shown in Figure 3.1. The process was as follows:

- A sample of crash data with the necessary details (e.g. travel speed, impact speed, braking time) was extracted from an appropriate database
- A model of the effects of ISA was developed
- The model was applied to the crash data to predict the effect ISA would have on impact speeds
- The effect of the reduced impacts speeds in lowering the probability of fatal and serious injuries (FSIs) was calculated using injury risk curves
- The effects of drivers ignoring or overriding the ISA system were accounted for using several modification factors
- The benefit of ISA was estimated by comparing the sum of the probabilities of FSI without ISA to the sum of the probabilities of FSI with ISA.

Each of the elements shown in Figure 3.1 will be described in detail in the following subsections.

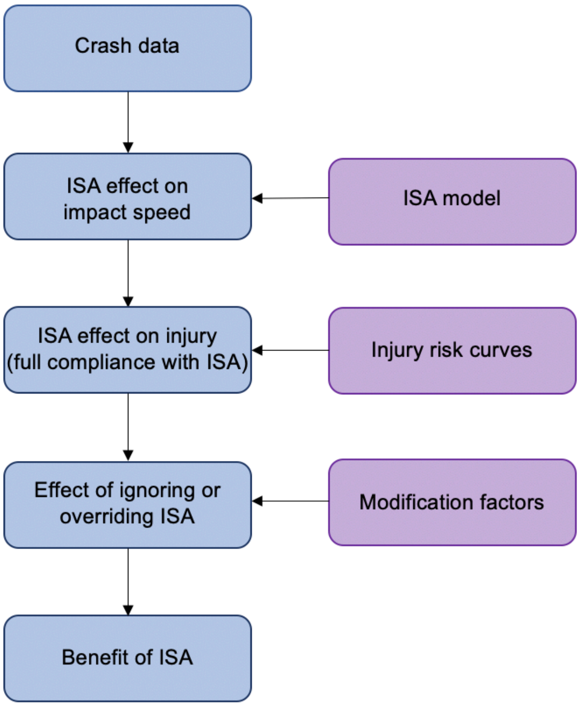

Figure 3.1
Methodological flow of estimating the safety benefit of ISA

3.1 Data source and case selection

The data source for the analysis was the CASR-EDR database. This database combines data extracted from the Event Data Recorder (EDR) of crashed vehicles with matched police reports. This process results in accurate knowledge about pre-crash speeds along with the speed limit where the crash occurred such that incidents of speeding can be determined. The cases within the CASR-EDR database are obtained from two sources; a sample of written of vehicles in an auction holding yard and vehicles involved in life-threatening crashes that are investigated by the South Australia Police's Major Crash Unit (Major Crash). As the two different sources have unequal coverage, the cases obtained from Major Crash were weighted to account for their overrepresentation of fatal and near fatal crashes. More detail on the CASR-EDR database can be found in Elsegood, Doecke & Ponte (2020a).

Suitable cases from the CASR-EDR database were selected based on two criteria. First, the EDR data was from a striking vehicle, meaning details about initial travel speed and impact speed were known. Secondly, the EDR data had to be from a crash type where there is a known relationship between travel speed and injury risk. This included right angle, right turn, rear end, head on, hit parked vehicle, pedestrian, and single vehicle crashes. Hit animal crashes, side swipes, and crashes where the vehicle was reversing did not meet this criterion.

The EDRs record pre-crash data, including travel speed and brake use, for up to five seconds preceding a collision. This allows for a precise understanding of a vehicle's travel speed, impact speed, and braking behaviour that can be used to model the crash sequence and the effect of an ISA system on it.

3.2 Intelligent Speed Adaptation (ISA) system model

For each case in the study sample, the original travel speed and impact speed are known from the EDR data. The time when braking started, and the level of braking can also be calculated from the EDR data. In cases where there was speeding, ISA is assumed to reduce the initial travel speed of the vehicle. Standard equations of motion are then used to determine a new impact speed, taking into account the start of braking time and the level of braking employed by the driver in the original crash. For cases where the driver of a vehicle applied braking before a crash occurred, the initial start–of–braking time can be calculated using the method outlined in Elsegood et al. (2020) and summarised in Appendix A.

The equation used to model the effects of ISA was developed in the following way. Consider a situation in which a vehicle is travelling along a road in a straight line when a situation arises that the driver needs to react to and start braking, such as a vehicle turning from a side street or stationary traffic ahead. This situation can be replicated for two distinct scenarios; one in which the vehicle is speeding and one in which the vehicle is travelling at the speed limit. Figure 3.2 presents a diagram of these two scenarios using the horizontal axis as a representation of distance. The top section refers to a vehicle travelling above the speed limit. The bottom section refers to the vehicle travelling at the speed limit due to ISA. Point A represents the distance at which the driver needs to react and start braking and Point C represents the collision point. Points B1 and B2 represent the locations where the vehicles start braking in each scenario. Point B2 is assumed to occur at a greater distance that Point B1 due to the slower initial travel speed in that scenario.

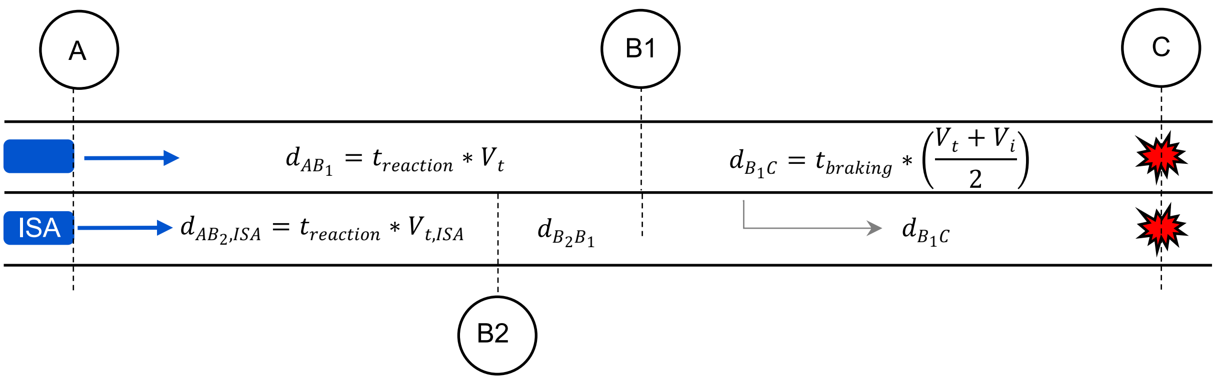

Figure 3.2
Diagram of pre-impact distances and braking points of a speeding vehicle and an ISA vehicle travelling at the speed limit

The equations below use the principle that distance is equal to velocity multiplied by time, where:

- d_{XY} represents the distance between a point (e.g. point X) and another point (e.g. point Y)
- $t_{reaction}$ is the time it takes for the driver to react to the situation and start braking,
- $t_{braking}$ is the time that the driver spent braking before the collision, as determined from the EDR data (shown in Appendix A),
- V_t is the original travel speed,
- $V_{t,ISA}$ is the new, ISA limited travel speed, and
- V_i is the original impact speed.

Simple subtraction between d_{AB_1} and $d_{AB_2,ISA}$ allows the calculation of $d_{B_2B_1}$:

$$d_{B_2B_1} = d_{AB_1} - d_{AB_2,ISA} = t_{reaction} * \left(V_t - V_{t,ISA}\right) \quad (1)$$

The distance from Point B2 to C is calculated using Equation 2:

$$d_{B_2C} = d_{B_2B_1} + d_{B_1C} = t_{reaction} * \left(V_t - V_{t,ISA}\right) + t_{braking} * \left(\frac{V_t+V_i}{2}\right) \quad (2)$$

To calculate the impact speed of the ISA vehicle, $V_{i,ISA}$, the following motion equation is used:

$$V_{i,ISA}{}^2 = V_{t,ISA}{}^2 + 2 * a * d_{B_2C} \quad (3)$$

The acceleration, a, is the average deceleration of the vehicle whilst braking, which is assumed to be equivalent to the average deceleration of the vehicle in the original situation:

$$a = \frac{V_i - V_t}{t_{braking}} \quad (4)$$

Combining Equation 4 with Equation 3 gives:

$$V_{i,ISA}{}^2 = V_{t,ISA}{}^2 + 2 * \frac{V_i - V_t}{t_{braking}} * d_{B_2C} \quad (5)$$

And then combining Equation 2 with Equation 5 gives:

$$V_{i,ISA}{}^2 = V_{t,ISA}{}^2 + 2 * \frac{V_i - V_t}{t_{braking}} * t_{reaction} * \left(V_t - V_{t,ISA}\right) + t_{braking} * \left(\frac{V_t+V_i}{2}\right) \quad (6)$$

Rearranging Equation 6 gives the following formula for the impact speed of the vehicle with ISA, $V_{i,ISA}$:

$$V_{i,ISA} = \sqrt{V_{t,ISA}^2 + 2\left(\frac{V_i - V_t}{t_{braking}}\right)\left(\frac{t_{braking}(V_t+V_i)}{2} + t_{reaction}\left(V_t - V_{t,ISA}\right)\right)} \quad (7)$$

- $V_{i,ISA}$ is the new impact speed with limiting ISA,
- $V_{t,ISA}$ is the new initial travel speed with limiting ISA (for speeding cases, the speed limit),
- V_i is the original impact speed,
- V_t is the original travel speed,
- $t_{braking}$ is the original time to collision when braking commenced, and
- $t_{reaction}$ is the reaction time.

A reaction time of 1.5 seconds was used for all cases that involved braking, as suggested by a literature review conducted by Green (2000). This is an average value of those found in experiments. It may be higher for elderly, impaired or inattentive drivers, and lower for young and/or highly attentive drivers.

Some ISA trials involving limiting or supportive ISA found that these systems, while reducing the speed of vehicles exceeding the speed limit, can increase the speed of vehicles travelling just below the speed limit. The potential effect of this phenomenon was investigated by increasing the travel speed of vehicles that were travelling at a free speed 5 km/h or less below the speed limit to the speed limit. The impact speed is then calculated according to Equation 7.

Advisory ISA systems usually have a small tolerance to speeding before the alert tone is activated so as to not overly annoy drivers trying to drive at the speed limit. A tolerance of 3 km/h was assumed for the advisory ISA model, meaning that crashes where the driver was speeding by 3 km/h or less were unaffected by the advisory ISA model. The sensitivity of the results to this tolerance was explored.

3.3 Injury risk reduction

The output of the ISA model is a set of new impact speeds that can be compared to the original impact speeds. Impact speed has been shown have a strong positive relationship to the risk of serious injury. These relationships can be used to calculate the original risk of serious injury in the sample of crashes and a new risk with the impact speeds determined by the ISA models. Comparing the new risk to the original risk will reveal the estimated benefits of ISA.

The risk of fatal and serious injury varies by impact type (Doecke, Baldock, Kloeden and Dutschke, 2020), and so separate injury risk curves were selected for each impact type included in the sample. These impact types included head on, side, front, rear, hit fixed object, and pedestrian impacts. No single source provided injury risk curves for all impact types.

The risk curves developed by Doecke *et al.*, (2020) were chosen for crashes involving an impact between two vehicles (head on, side, front, and rear impacts). These risk curves were developed from a sample 1,274 crashes where impact speed and injury details were known. They are also the only risk curves available at this time which provide absolute risk of serious and fatal injury (AIS3+) as a function of impact speed for these impact types. These risk curves are shown in Figure 3.3, and the equations for these risk curves are shown in Equations 8 to 11.

$$P(v_{impact,front}) = \frac{1}{1+e^{8.1231-0.0548v_{impact,front}}} \quad (8)$$

$$P(v_{impact,headon}) = \frac{1}{1+e^{7.3881-0.0964v_{impact,headon}}} \quad (9)$$

$$P(v_{impact,side}) = \frac{1}{1+e^{10.5583-0.1161v_{impact,side}}} \quad (10)$$

$$P(v_{impact,rear}) = \frac{1}{1+e^{12.1538-0.1119v_{impact,rear}}} \quad (11)$$

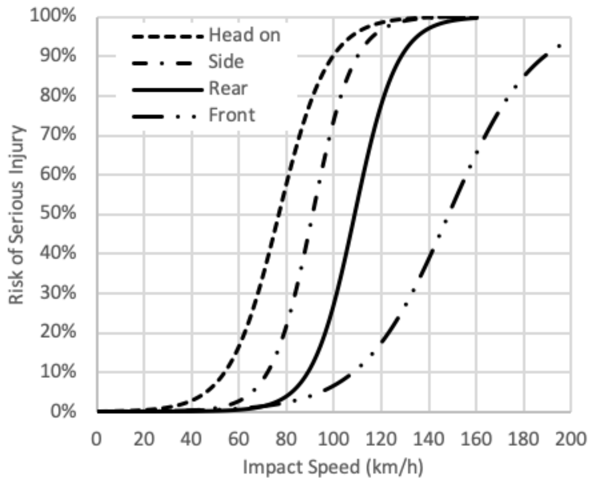

Figure 3.3
Risk curves from Doecke *et al.* 2020 relating risk of fatal and serious injury to impact speed, by impact configuration.

The Doecke *et al.* injury risk curves must be applied separately for each vehicle involved in a collision. For example, in a rear-end crash there is one vehicle that has a front impact and one that has a rear impact. To calculate an overall injury risk for a multi-vehicle crash, the individual per-vehicle risks can be summed according to Equation 12.

$$P(FSI_{crash}) = P(FSI_{unit\ 1}) + P(FSI_{unit\ 2}) - P(FSI_{unit\ 1}) \times P(FSI_{unit\ 2}) \qquad (12)$$

The risk of fatal and serious injuries for pedestrian crashes was calculated according the relationships found in Davis (2001), as shown in Equation 13.

$$P(v_{impact,pedestrian}) = \frac{1-e^{4.68-0.12v_{impact,pedestrian}}}{1+e^{4.68-0.12v_{impact,pedestrian}}} \qquad (13)$$

For collisions with fixed objects the risk curve from Augenstein (2003), that relates the change in velocity (delta-v) to risk of fatal and serious injury (AIS3+) was used (Equation 14). Note that in Equation 14, delta-v is in miles per hour.

$$P(\Delta v_{fixed\ object}) = \frac{1}{1+e^{4.1373-0.1228\Delta v_{fixed\ object}-0.3144}} \qquad (14)$$

The CASR-EDR data contained delta-v for each case which was used to calculate the original probability of fatal and serious injury according to Equation 14. Equation 15 was used to calculate the ISA delta-v which was then used in Equation 14 to determine the probability of fatal and serious injury with ISA.

$$\Delta v_{ISA} = \frac{\Delta v \times v_{ISA}}{v} \qquad (15)$$

The output of this step is a probability of fatal and serious injury for each crash with ISA and without ISA.

3.4 Modification factors

Only limiting ISA systems force drivers to obey the speed limit. Advisory ISA do not restrict drivers to the speed limit but merely inform people when they have exceeded the speed limit. Some advisory systems may also provide an incentive to return to the speed limit through repetition of an alert tone. Supportive ISA does limit drivers to the speed limit but can be overridden.

The results of the literature review (Section 2) were used to guide the selection of modification factors to be applied to reductions in injury risk calculated in the previous step. These modification factors were selected as a range, with upper and lower limits based on the limited literature available. The modification factors are expressed as a number between zero and one, where zero would represent the case where 0% of drivers would comply with the speed limit despite having advisory or supportive ISA in their vehicle, and one representing the case where 100% of drivers would comply with the speed limit as a result of these ISA systems. As none of the literature explored combinations of factors influencing compliance with an advisory system, the modification factors were treated independently and only the factor with the lowest modification was applied to a given crash: the factors were not multiplicative.

The modification factors for advisory ISA are shown in Table 3.1 The "general" modification factor represents a general reduction in effectiveness that applies to all cases. A driver who was speeding by more than 15 km/h was assumed to be deliberately speeding and was therefore considered unlikely to respond to the warnings of an advisory ISA system. Regular speeders were identified by their offence history within the last 5 years from the date of the crash. If a driver had three or more speeding offences, or an offence that involved exceeding the speed limit by 30 km/h or more within this time period they were classified as a regular speeder for the purpose of this study. A driver who was overtaking was assumed to be highly unlikely to respond to an advisory ISA system.

Table 3.1
Modification factors for advisory ISA

Factor	Modification lower limit	Modification upper limit
General	0.85	0.95
Age ≤ 25	0.6	0.8
Male driver	0.8	0.9
Speeding > 15 km/h	0.25	0.5
Regular speeder	0.4	0.7
Overtaking	0.0	0.1

The modification factors for supportive ISA are shown in Table 3.2. As supportive ISA can only be overridden with a deliberate action, rather than just ignored, the modification factors were based on indications of deliberate and/or regular speeding. These included speeding by more than 15 km/h, being a regular speeder according to speeding offence history, and overtaking. As supportive ISA is more difficult to override the modification factors for supportive ISA are higher than those for advisory ISA.

Table 3.2
Modification factors for supportive ISA

Category	Modification lower limit	Modification upper limit
Speeding > 15 km/h	0.4	0.7
Regular speeder	0.8	1.0
Overtaking	0.0	0.1

These modification factors were applied to the reduction in serious injury probability that was determined by the method described in Section 3.2 and 3.3. For example, the ISA model and subsequent probability of fatal and serious injury calculations predicted that the risk of serious injury would be reduced from 4% to 2%, and the advisory ISA modification factor was 0.6, the risk of serious injury would be 2.8%.

3.5 Determining the benefit of ISA

The final step of the process is to use the results of Sections 3.2 to 3.5 to determine the benefit of ISA for the whole sample of crashes. These sections have described how a probability of fatal and serious injury can be calculated for each case using the original impact speed, and the ISA impact speed. To determine the overall benefit the probabilities are summed to produce the predicted number of fatal and serious injuries in the sample. The same is done for all the crashes using the new impact speeds produced by the ISA model. By comparing the predicted number of fatal and serious injuries with and without ISA the benefit of ISA, with respect to reductions in fatal and serious injuries, is estimated.

3.6 Example case

The following is an example of how this method worked for one of the crashes in the sample.

A vehicle was involved in a rear end crash (See Figure 3.4). The EDR download from the vehicle, (shown in Figure 3.5) revealed that it was travelling at 66 km/h 2.1 seconds before impact. The matched police report revealed that this crash occurred in a 60 km/h zone, therefore this vehicle was travelling 6 km/h above the speed limit. The police report also revealed it was the striking vehicle in a rear end crash. The start of braking time was determined to have been 1.25 seconds before impact (see Appendix A). This braking slowed the driver to 40 km/h at impact. The bottom row in Figure 3.5 shows the distance from the collision point (calculated post-download). The distance from the impact point when the vehicle started to brake was calculated to be 18.3 metres.

Figure 3.4
Crashed vehicle from example case

Time (sec)	-4.1	-3.1	-2.1	-1.1	-0.1	0 (TRG)
Vehicle Speed (MPH [km/h])	37.3 [60]	39.8 [64]	41 [66]	39.8 [64]	24.9 [40]	24.9 [40]
Brake Switch	OFF	OFF	OFF	ON	ON	ON
Accelerator Rate (V)	1.29	1.41	1.41	0.78	0.78	0.78
Engine RPM (RPM)	1,200	1,200	1,200	1,200	800	800
Distance to crash (m)	68.9	51.7	33.6	15.5	1.1	0

Figure 3.5
EDR data downloaded from crashed vehicle

The diagram in Figure 3.6 demonstrates the distances travelled by the striking vehicle during the crash and in the counter-factual scenario where the driver had a limiting ISA system installed. At point A along the road an event occurs that the driver needs to react to. At point B1 and B2 the vehicles begin to brake in response, and point C represents the impact point.

The travel speeds and distances during the crash are shown in Figure 3.6. The vehicle was originally travelling at 66 km/h. The distance from point A to point B1 was calculated to be 27.5 metres (66 km/h multiplied by the reaction time of 1.5 seconds), and the distance from point B1 to point C was calculated to be 18.3 metres. Thus, the total distance from point A to point C was 45.8 metres.

For the ISA case, the initial speed and start–of–braking speed is set to the speed limit of 60 km/h. Therefore, between point A and point B2, the travel speed of the ISA vehicle is 60 km/h. The same reaction time applies but, as the travel speed is lower, the distance from point A to point B2 is calculated to be 25 metres. The distance from point B2 to point C is consequently 20.8 metres, based on the total distance calculated previously (45.8 metres minus 25 metres). From point B2 to point C, the average deceleration from the original case between point B1 and C (0.59g), and the new impact speed is calculated to be 22 km/h.

This example shows how a modest reduction in travel speed can result in a much greater reduction in impact speed. In this case the reduction in impact speed was 18 km/h, or three times the reduction in travel speed of 6km/h.

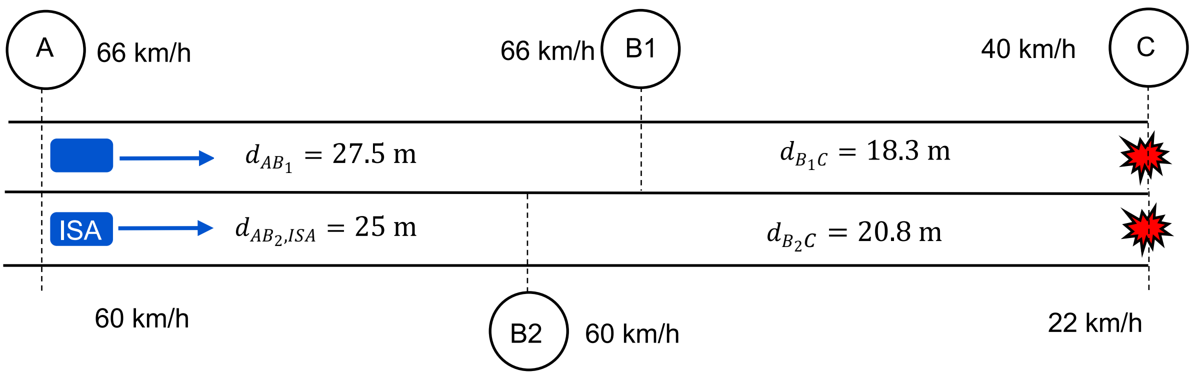

Figure 3.6
Comparison of original vehicle and ISA equipped vehicle before collision

The original serious injury risk of this crash with an impact speed of 40 km/h was calculated to be 0.31%. When the impact speed is reduced to 22 km/h with limiting ISA the risk reduces to 0.1%. This serious injury risk remains 0.1% with supportive ISA as no modification factors were applicable. With advisory ISA, a modification factor was applied to the risk reduction as the driver was 25 years old (lower limit of 0.6 and upper limit of 0.8). The risk with advisory ISA was calculated to be between 0.14 and 0.19%.

4 Results

4.1 Sample characteristics

A total of 215 cases met the selection criteria. Of these, 65 (30%) involved vehicles were speeding. Drivers that were speeding made up an increasing percentage of the total cases as injury severity increased (Table 4.1). In total, there were 26 cases that resulted in serious injuries (admitted to hospital) or a fatality, and half of those involved speeding.

Table 4.1
Striking vehicles that met the selection criteria by speeding

Injury severity	Not speeding	Speeding	Total	% Speeding
Property damage only	81	26	107	24%
Treated by doctor	3	2	5	40%
Treated at hospital	53	24	77	31%
Admitted to hospital	7	5	12	42%
Fatal	6	8	14	57%
Total	150	65	215	30%

Table 4.2 shows the cases by speed limit and speeding. Just under half occurred in 60 km/h zones, and around a quarter occurred in high speed zones. The percentage of cases where the vehicle was speeding was lowest in 60 km/h zones, and highest in the rarer speed zones of 40, less than 40, and 90 km/h. Of the common speed zones, 50 km/h zones had the highest percentage of speeding.

Table 4.2
Speeding by speed limit

Speed limit	Not speeding	Speeding	Total	% Speeding
<40 km/h	0	2	2	100%
40 km/h	2	3	5	60%
50 km/h	27	19	46	41%
60 km/h	84	21	105	20%
70 km/h	3	2	5	40%
80 km/h	15	6	21	29%
90 km/h	1	4	5	80%
100 km/h	9	4	13	31%
110 km/h	9	4	13	31%
Total	150	65	215	30%

The degree to which the 65 speeding vehicles were travelling over the speed limit is shown in Table 4.3. While a third were travelling 5 km/h or less over the speed limit, just under half were travelling more than 10 km/h over the limit. There were 14 (22%) that were travelling more than 30 km/h over the speed limit, with 6 of these being more than 50 km/h over and 2 more than 100 km/h over the limit.

Table 4.3
Degree of speeding

Speeding severity	Number	Percentage
1-5 km/h	21	32.3%
6-10 km/h	12	18.5%
11-15 km/h	8	12.3%
16-20 km/h	6	9.2%
21-30 km/h	4	6.2%
30+ km/h	14	21.5%
Total	65	100.0%

Table 4.4 shows the characteristics of the speeding cases used to model the effectiveness of advisory and supportive ISA. More males than females were speeding. A third of speeders were 25 years old or younger, only 3% were aged over 65 years old. Most of the drivers that were speeding were not classified as regular speeders according to their speeding offence history. Only one of the speeding vehicles was overtaking at the time of the crash.

Table 4.4
Characteristics of the speeding cases used to model advisory and supportive ISA

Characteristic	Number	Percentage
Sex		
Female	24	37%
Males	39	60%
Unknown	2	3%
Age		
<26	21	32%
26-65	40	62%
>65	2	3%
Unknown	2	3%
Regular speeder		
Yes	13	20%
No	52	80%
Overtaking		
Yes	1	2%
No	64	98%
Total	65	100%

4.2 Benefits of ISA

Crashes avoided

A crash was considered avoided if the new impact speed was calculated to be zero. The crashes that would be completely avoided with ISA are shown in Table 4.5. A total of 15 of the 215 crashes would be avoided with limiting ISA. This reduced to an estimated 10.3 to 12 with supportive ISA and 5.85 to 9.1 with advisory ISA. Importantly, 2 of the 14 fatal crashes would have been completely avoided had the vehicle been travelling at the speed limit. It is possible that more crashes than is shown here could have been avoided as their slower speed may have allowed the struck vehicle to move out of the striking vehicles path before the striking vehicle reached the impact point.

Table 4.5
Crashes avoided with ISA

Injury severity	Limiting ISA		Supportive ISA		Advisory ISA	
	Crashes avoided	% of total	Crashes avoided	% of total	Crashes avoided	% of total
Property damage only	9	8.3%	6.0 – 7.0	5.6 – 6.5%	3.40 – 5.35	3.1 – 5.0%
Treated by doctor	0	0.0%	0	0.0%	0	0.0%
Treated at hospital	3	3.8%	1.5 - 2.0	1.9 – 2.6%	0.75 - 1.50	1.0 – 1.9%
Admitted to hospital	1	8.3%	1.0	8.3%	0.85 - 0.95	7.1 – 7.9%
Fatal	2	14.3%	1.8-2.0	12.9 -14.3%	0.85 - 1.30	6.1 – 9.3%
Total	15	6.9%	10.3 - 12	4.8 - 5.5%	5.85 - 9.1	2.7 – 4.2%

Note: there were also two crashes (treated at hospital in severity) that had their impact speed reduced to 1 km/h

Effect on speeds

The change in impact speed distribution if all vehicles were travelling at the speed limit due to limiting ISA is shown in Figure 4.1. The average impact speed reduction was 24.9 km/h, with a median value of 18 km/h. Limiting ISA eliminated impacts that occurred above the speed limit, leading to an increase in impacts at, or just below, the speed limit. Limiting ISA also increased the number of impacts that occurred at more than 39 km/h below the speed limit.

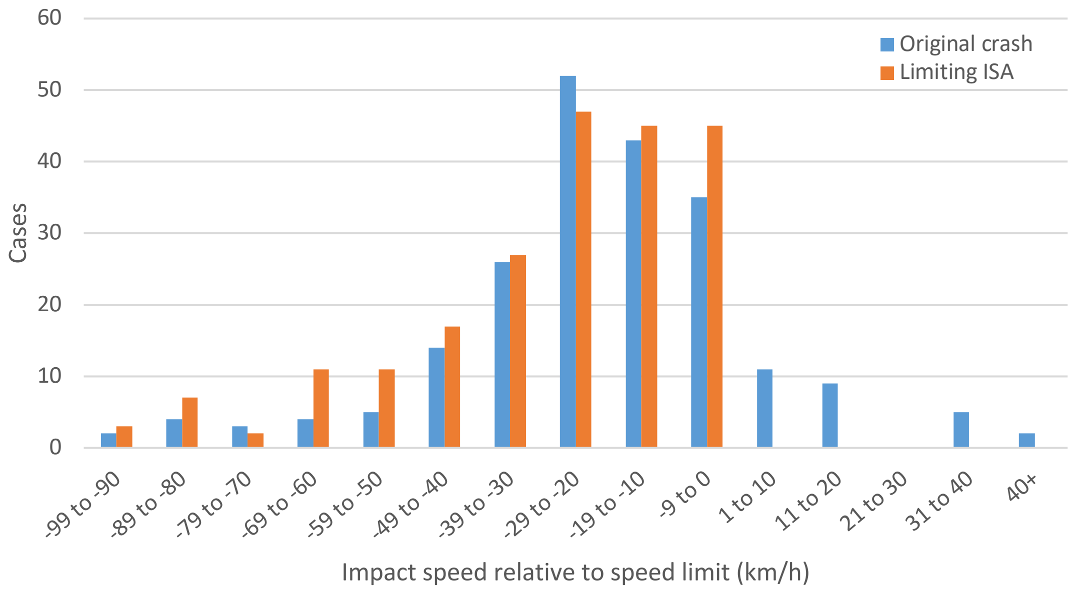

Figure 4.1
Distribution of impact speed relative to speed limit with and without limiting ISA

Crash reductions

Prior to weighting the Major Crash cases, the total number of predicted fatal and serious injuries without ISA was 22.6. This compares to 26 in the actual sample. This difference is most likely related to a difference in the definition of a serious injury crashes. Serious injuries in the police data are defined as someone being admitted to hospital, while in the risk curves used to predict serious injury it is defined as an AIS3+ injury. It is likely that some patients admitted to hospital did not suffer an AIS3+ injury therefore it is not unexpected that the predicted number of AIS3+ injuries is lower than the number of fatal and hospital admission crashes in the sample.

Table 4.6 shows the reduction in expected numbers of serious injuries with the different types of ISA. Limiting has the highest reduction, with 17.6% (after weighting), followed by supportive (8.1% to 12.3%) and advisory (5.1% to 9.0%). Testing of the scenario where limiting and advisory ISA caused drivers travelling at a free speed close to the speed limit to increase their speed to the limit revealed that this only changed the reduction in serious injuries by 1.1 percentage points.

Table 4.6
Reductions in serious injury with different types of ISA

ISA type	Projected serious injuries	Unweighted % reduction	Weighted % reduction	% reduction with speed increase
None	22.6	-	-	-
Limiting ISA	18.4	18.7%	17.6%	16.5%
Supportive ISA	19.2 – 20.0	11.3 – 15.1%	8.1 – 12.3%	7.0 – 11.2%
Advisory ISA	20.2 – 21.1	6.6 – 10.6%	5.1 – 9.0%	-

Sensitivity to speeding tolerance

The sensitivity of the benefit of advisory ISA to the tolerance, the level before the warning is activated, is shown in Figure 4.2. When there is no tolerance (0 km/h) the benefit ranges from 6 to 10.2%. This reduces to 4.7 to 8.3% when the tolerance is increased to 4 km/h. It should be noted that the specific results shown here may be influenced by the sample size, which is small when broken down by each km/h travelled over the speed limit. It is therefore difficult to be certain about an overall trend in the sensitivity even though it appears that most of the loss in benefit occurs in the first 4 km/h.

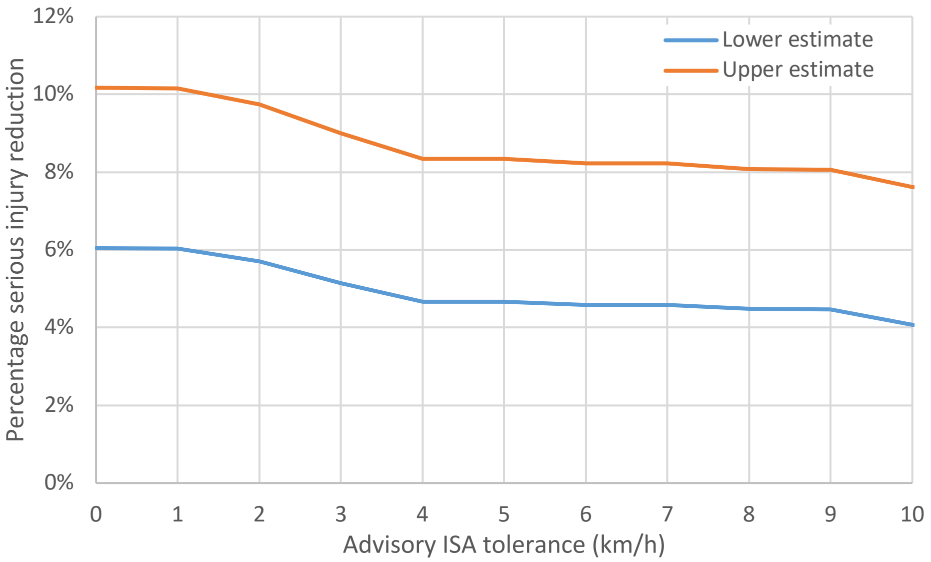

Figure 4.2
The sensitivity of the benefit of advisory ISA to the tolerance before the alert sounds

5 Discussion

This study used a sample of real-world crashes with EDR data to predict a reduction in impact speed and estimate the percentage reduction in serious injury crashes that could be achieved if all vehicles were equipped with ISA. Newly developed risk curves, relating impact speed and the risk of serious injury, were used to calculate the change in serious injury risk. It was found that limiting ISA could reduce serious injuries by 17.6%, with supportive ISA systems producing an 8.1% to 12.3% reduction and advisory ISA a 5.1 to 9% reduction. If these reductions were applied to the 40,000 serious injury crashes (hospitalisation crashes) that occur each year in Australia this would represent 7,040 less serious injury crashes with limiting ISA, 3,240 to 4,920 less with supportive ISA, and 2,040 to 3,600 less with advisory ISA each year.

Comparison with previous Australian studies

The percentage reductions found in this study are lower than those found in previous Australian studies. Doecke *et al.* (2010) applied the change in speed profiles found in the ISA-UK study to Australian speed profiles and found that ISA could reduce injury crashes by 26.4% with a limiting system, 15.1% with a supportive system, and 7.7% with an advisory system. Creef *et al.* (2011) used the change in speed distributions reported by the NSW ISA trial to estimate that advisory ISA could reduce serious injury crashes by 19.2%. Both Doecke *et al.* (2010) and Creef *et al.* (2011) calculated these reductions by applying the relative risk curve developed by Kloeden *et al.* in 1997 to speed distributions, while the present study used the absolute risk curves developed by Doecke *et al.* (2020), Augenstein *et al.* (2003) and Davis (2001). There are several differences between the risk curves used in the present study, and those used in the earlier studies. The Kloeden risk curve does not distinguish between accident types, unlike the present study that used separate risk curves for different impact types. Kloeden *et al.,* being over 20 years old, was based on crashes involving much older vehicles that predated passive safety developments such as airbags and drastically improved crashworthiness (driven by progressively more stringent NCAP assessment criteria), potentially resulting in a steeper risk curve and a larger crash risk reduction for a given change in speed.

The large difference between the effectiveness of advisory ISA found in Creef *et al.* (2011) and this present study may also be, in part, due to the respective samples. The sample of drivers involved in the NSW ISA trial may be different to those involved in the crashes in the CASR-EDR sample. Of the drivers in the NSW trial 10% were classified as a deliberate speeder due to answers they gave in a questionnaire. This is much lower than the results of a survey on speeding by Stephens *et al.,* (2017) that classified 56% of drivers as speeders and 20% as mid to high level speeders. Advisory ISA has been found to be least effective for those that need it most, and these types of drivers may have been under-represented in the NSW trial. It is also worth noting that the ISA system used in the NSW ISA trial provided no tolerance, with an alert being provided as soon as the driver exceeded the speed limit. In contrast, the present study assumed that an advisory system would only alert the driver when they were driving more than 3 km/h over the speed limit. It is considered unlikely that drivers would accept a system with no tolerance. Indeed, NCAP protocols on advisory ISA require a 5 km/h tolerance before a warning is sounded. Both the differences in the sample of drivers and the tolerance before warnings are given may have contributed to the difference in the results of Creef *et al.* (2011) and the present study.

Considerations for ISA implementation

The benefits that have been demonstrated in this study, and previous studies that included cost benefit analyses (Doecke, Anderson and Woolley, 2010), suggest that it would be worthwhile for Australia to mandate some form of ISA. The European Union has included mandatory ISA in a suite of new vehicle regulations focussed on active safety systems. While the regulation only mandates advisory ISA as a minimum, it does require that it is activated every time the vehicle ignition is turned on. Of the new vehicles sold in Australia in 2019, only 6% had an ISA system fitted as standard, with a further 4% of vehicles offering it as an option (IHS Markit). Mandating fitment of ISA would speed up penetration of ISA in the fleet and ensure that it is fitted as standard on all models of vehicles rather than being an option or only on certain variants.

Regulation would also ensure suitable minimum specifications for ISA systems. The specific design of supportive and advisory ISA systems may influence how effective they are at reducing speeds and serious injury crashes. A recent simulator study (Carsten, Ezenwa, Tomlinson & Horrobin, 2020) compared the speed compliance and user ratings of different types of advisory and supportive ISA systems. The advisory systems used an auditory warning or a vibrating pedal, while the supportive systems used a haptic pedal, speed control, and speed control with a vibrating pedal. They found that speed compliance results were similar for each type, though the vibrating pedal was the most effective. However, they also found this design to be the most annoying for drivers, suggesting it would be the most likely to be deactivated. The authors concluded that the speed control, haptic pedal, and speed control with vibrating pedal types had reasonable acceptance and effectiveness. It should be noted that no tolerance to the speed limit was used in the simulator study conducted by Carsten *et al.* (2020). It is unlikely that an auditory warning system would be used without a tolerance. The present study found that allowing a tolerance does decrease the benefit of the system. A tolerance of 2 km/h (warning sounds at 3 km/h over the limit) may represent a good compromise between reducing annoyance and the resultant system deactivations and maximising the benefit of an advisory system. It is also worth noting that the types of ISA that Carsten *et al.* (2020) found to be most acceptable to users were all supportive type systems. Supportive systems have also been shown in this study, and in previous on-road trials (ISA-UK), to produce greater benefits than advisory systems. This suggest that well designed supportive ISA systems should be the focus of future promotion and/or regulation.

This study, and previous on road trials, have found that limiting ISA is the most effective, followed by supportive and advisory ISA. However, the main ISA systems that have been installed on production vehicles are either supportive or advisory, as consumers may not accept a system that cannot be turned off. Previous research has also found that those who would benefit most from ISA (especially limiting ISA), including those with a propensity to speed, are the least accepting of it (Vlassenroot *et al.* 2011). This could result in the drivers that would most benefit from ISA simply turning it off in their vehicle. Some consideration should therefore be given to installing limiting ISA on vehicles of repeat or high-level speed offenders, much like the alcohol interlock schemes that have been introduced in Australia over the last decade.

Implementation of limiting ISA would require ISA systems that make less speed limit errors than current systems. ISA systems identify the speed limit using traffic sign recognition systems, GPS based speed limit maps, or a combination of these methods. A recent Austroads report (Roper *et al.*, 2018) highlighted problems that traffic sign recognition systems encounter with Australian speed limit signs. These included reading electronic signs, mistaking signs placed on side roads or off-ramps as applying to the current road, and conditional signs such as timed school zones. The authors of this report have also had access to raw data from ISA trials that used GPS based speed limit maps. We noted that errors can occur when driving on a road that has a parallel road in close proximity, and around bridges. These maps also need to be kept up to date when changes are made to speed limits. CASR has two vehicles in its fleet equipped with ISA, one factory fitted, and the other an aftermarket device. Misidentification of speed limits has been noted to be a relatively common occurrence with either system. While misidentification of the speed limit when driving with an advisory or supportive ISA would be an annoyance, limiting a driver to a lower, and potentially much lower, speed could potentially be dangerous. The Austroads report by Roper *et al.* (2018) suggested that the accuracy of traffic sign recognition systems, and therefore ISA system, could be improved by traffic sign standards that take these systems into account, and improvements from manufacturers in the spatial awareness of such systems. If these improvements can be made, implementing limiting ISA could be feasible in the future.

Limitations of the methodology

One limitation of the method is that it only considers a crash as fully avoided when the striking vehicle's speed is reduced to zero at or before the impact point. In some situations, a crash may be avoided due to the slowing of the striking vehicle allowing the struck vehicle to clear the path of the striking vehicle before it arrives at the original impact point. In particular, this would apply to right angle and right turn type crashes where the struck vehicle is moving across the path of the striking vehicle. From this perspective, the results can be considered conservative.

The models of advisory and supportive ISA were limited by the scarcity of literature that examined predictors of compliance. Of those that did, some produced somewhat conflicting results. This made the process of selecting the categories for which to apply modifications factors, and the size of these modification factors difficult. The relatively large range used for certain modification factors was due to this uncertainty. It is also possible that other predictors exist that have not yet been identified.

Another limitation of the method is that an average reaction time was used for all crashes. Reaction time is the one variable in the equation for ISA impact speed that cannot be determined from the EDR data. If the reaction time of the driver in the actual crash was larger than the 1.5 second average reaction time used in the method, the result would be an underestimate of the actual impact speed reduction that would be achieved with. This could particularly be the case if the driver was elderly, impaired due to being under the influence of alcohol or drugs, or if they were not paying attention to the driving task. For crashes where the actual reaction time was lower than the assumed value the impact speed the result would be an overestimate of the speed reduction with ISA. The effect of this limitation on the overall result is unknown.

6 Conclusions and Recommendations

It was found that ISA can result in substantial reductions in impact speed in a crash, and if all vehicles were fitted with ISA:

- Limiting ISA could reduce serious injuries by 17.6%, or 7,040 per year in Australia.
- Supportive ISA could reduce serious injuries by 8.1 to 12.3%, or 3,240 to 4,920 per year.
- Advisory ISA could reduce serious injuries by 5.1 to 9%, or 2,040 to 3,600 per year

Supportive ISA systems appear to be the best ISA type for regulation, having shown strong user acceptance in other studies, and moderate safety benefits in this study and previous studies.

Consideration should be given to mandating Limiting ISA for repeat speed offenders once technical limitations have been overcome, as these are the drivers that will benefit from ISA the most but are the most likely to ignore an advisory or supportive system that can be over-ridden.

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Appendix A – Derivation of start–of–braking time equation

The derivation of the formula used to calculate the start–of–braking time is shown below.

The following Figure shows a snippet of an EDR output from a crash-involved vehicle. The braking timesteps of the vehicle before the crash are shown in the top row, followed by the vehicle speed in the next row. The brake status is also included in the second from the bottom row.

Time (sec)	-2.25	t_1 -1.75 t_s	-1.25 t_2	-0.75 t_3	-0.25	0 (TRG)
Vehicle Speed (MPH [km/h])	59.7 [96]	V_1 60.9 [98] V_s	55.3 [89] V_2	45.4 [75] V_3	36.7 [59]	33.6 [54]
Accelerator Pedal, % Full (%)	39.5	0.0	0.0	0.0	0.0	0.0
Percentage of Engine Throttle (%)	33.0	1.5	0.0	0.0	0.0	0.0
Engine RPM (RPM)	3,900	3,900	3,100	2,300	1,700	1,500
Motor RPM (RPM)	Invalid	Invalid	Invalid	Invalid	Invalid	Invalid
Service Brake, ON/OFF	OFF	OFF	ON	ON	ON	ON
Brake Oil Pressure (Mpa)	0.00	0.00	6.77	9.12	9.36	9.70

The red and blue variables indicate the time and speed values used in the formulas and derivation.

The last timestep where braking is OFF is determined. This timestep has the variables assigned for time and speed: t_1 and V_1 respectively.

The timesteps following the previously determined timestep are where the braking is ON. These two timesteps are assigned variables for time and speed similarly, t_2 and V_2, and t_3 and V_3.

The start–of–braking time is between t_1 and t_2, so two variables, V_s and t_s, are created to be between the two timesteps to indicate the speed at the start of braking and the time at the start of braking.

The acceleration between two timesteps is equal to the change in velocity divided by the change in time. For the acceleration between timesteps 2 and 3, the equation is:

$$a_{2-3} = \frac{(V_3 - V_2)}{(t_3 - t_2)}$$

The acceleration between timesteps 2 and 3 may be considered to be roughly the same acceleration between the start of braking and timestep 2. Hence:

$$a_{s-2} = \frac{(V_2 - V_s)}{(t_2 - t_s)} = a_{2-3} = \frac{(V_3 - V_2)}{(t_3 - t_2)}$$

But it can be assumed that $V_s = V_1$ as the speed decrease before braking in a very short time would be negligible in most cases. Therefore:

$$\frac{(V_2 - V_1)}{(t_2 - t_s)} = \frac{(V_3 - V_2)}{(t_3 - t_2)}$$

Rearranging the equation to focus on t_s:

$$t_s = t_2 - \frac{(V_2 - V_1)(t_3 - t_2)}{(V_3 - V_2)}$$

Due to the negative time values of the timesteps, t_s needs to be converted to a positive value. A ramping time of 0.085 is also added to the braking time to account for the time it takes for the average driver to apply the brakes from 0% to the desired level. The equation then becomes:

$$t_s = \left| t_2 - \frac{(V_2 - V_1)(t_3 - t_2)}{(V_3 - V_2)} \right| + 0.085$$

Cases where the calculated braking start time is before the pre-braking timestep (with braking recorded as OFF) are assumed to have occurred in the milliseconds after the pre-braking timestep was recorded, resulting in a start braking time equal to the pre-braking time value, i.e. $t_s = t_1$.

Cases where there was no speed decrease between the timesteps of changing braking from OFF to ON were assumed to have the start of braking equal to the first post-braking time value, i.e. $t_s = t_2$.

Cases where the third timestep did not exist, i.e. where the braking was only ON for the impact timestep, another similar formula, equation 2, is used to calculate the start–of–braking time.

$$t_s = \left| t_2 - \frac{(V_2 - V_1)}{-28.25} \right| + 0.085$$

where:

- t_s is the start–of–braking time
- t_2 is the time relating to impact timestep where braking is ON
- V_1, V_2 are the speeds relating to timesteps where braking pattern is OFF, ON (V_1 is before V_2)
- -28.25 km/h per second is an acceleration value typical to heavy braking
- 0.085 is the ramping value.