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Evaluating changes in driver behaviour: A risk profiling approach

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ABSTRACT

New road safety strategies continue to be devised by researchers and policy makers with pay-as-you-drive (PAYD) schemes gaining increasing attention. However, empirically measuring the effectiveness of these strategies is challenging due to the influence of the road environment and other factors external to the driver. The analysis presented here applies Temporal and Spatial Identifiers to control for the road environment and Driver Behaviour Profiles to provide a common measure of driving behaviour based on the risk of a casualty crash for assessing the effectiveness of a PAYD scheme on reducing driving risks. The results show that in many cases personalised feedback alone is sufficient to induce significant changes, but the largest reductions in risk are observed when drivers are also awarded a financial incentive to change behaviour. Importantly, the more frequent the exposure to the speeding information, the greater the magnitude of the change. However, the changes are disproportionately associated with those that were already safer drivers in the baseline period suggesting that some drivers may be predisposed to changing their behaviour. These results suggest that it would be beneficial to provide real-time or daily feedback on speeding behaviour in conjunction with a financial reward scheme, potentially as a component of insurance premiums.

1. Introduction

New road safety strategies continue to be developed by researchers and policy makers. Of these, pay-as-you-drive (PAYD) reward/insurance schemes have gained increasing attention (see Elvik, 2014). PAYD provides financial incentives to motorists based on their driving behaviour to encourage reductions in speeding and other risky driving, or penalties for poor behaviour. However, empirically measuring the effectiveness of these strategies is a challenging task because behaviour is frequently influenced by the road environment, and road crashes – arguably the best indicator of risky driving – are rare even for the worst drivers. Naturalistic driving data–data collected using sensors during day-to-day driving – tend to be an intrinsic component in PAYD studies. However, direct comparisons are difficult due to the influence of external factors and the need to isolate the financial, education and other components of these schemes.

This paper reports on an examination of the effect on risky driving behaviour – speeding, acceleration and braking specifically – of increasing awareness of speeding behaviour and a financial reward as part of a PAYD study conducted on 106 drivers in Sydney, Australia (Greaves et al., 2010). The overall study consisted of several components including a financial reward for reducing speeding and, implicitly in the design of the study, individualised and daily feedback on the frequency of speeding behaviour. The analysis presented here applies Temporal and Spatial Identifiers (TSI) (Ellison et al., 2013) to control for the road environment and Driver Behaviour Profiles (DBP) (Ellison, 2014) to provide a common measure of driving behaviour based on the risk of a casualty crash for the purposes of comparing the change in behaviour between the before and after phases.

It can be argued that without controlling for the effect of spatiotemporal characteristics and incorporating different magnitudes of behaviour, an analysis of before-and-after data may be explaining changes in these factors rather than changes that occur as a consequence of the intervention. For example, Toledo et al. (2008) developed a method of assessing driver behaviour using naturalistic driving data which could then be used as both feedback for the driver and in before-and-after measurements. However, despite including 20 manoeuvres it does not control for changes in where and when driving occurred. In contrast, this paper controls for these factors and thereby isolates the influence of the driver. In so doing, it then becomes possible to assess the individual merits of increasing awareness and imposing a financial incentive to change behaviour. Furthermore, by using a measure of risk, this paper

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provides an indication as to the impact of PAYD schemes on the risks of involvement in a casualty crash itself as opposed to simply a measure of behaviour.

Background information and literature review is presented first, with a focus on feedback and financial incentives. This is followed by a description of the study design and data collection process. The methodology and data processing techniques applied are then outlined. Modelling results are then presented. The paper concludes with discussion and conclusions.

2. Background and literature review

Changing driver behaviour can be approached in a number of ways. Education campaigns are used to educate drivers about the consequences associated with particular behaviours on the premise that increased knowledge, and in some cases greater fear or shame of the consequences, will result in a beneficial change in behaviour. In other cases, drivers already know (or are assumed to know) the dangers associated with risky behaviours and, therefore, methods are used to make drivers aware of their own behaviour. This can be done in real time through an in-car device or retrospectively. There are a number of methods for providing this information including dynamic speed display signs (Gehlert et al., 2012; Roberts and Smaglik, 2012), passive in-vehicle Intelligent Speed Adaptation (ISA) devices fitted to vehicles, through smart-phone apps used within the vehicle that determine the actual speed and speed limit and provide audible and visual warnings when necessary, using active ISA[1] that physically pushes back on the accelerator when the driver is speeding (Várhelyi et al., 2004), or post-travel through a web-based system. These methods do not educate drivers on the risks they are taking but do increase awareness of how they are driving. The premise here is that at least some speeding behaviour is inadvertent (Corbett, 2001) and therefore mechanisms for making drivers aware of the extent to which they speed may encourage greater care to be taken.

Financial incentives (and disincentives) can also be used to encourage behaviour change. This method rewards drivers for not engaging in risky driving behaviour, such as speeding, or penalises them each time they engage in a specific behaviour through a monetary mechanism. Speeding fines are a crude example of a financial disincentive but more sophisticated programmes such as PAYD are becoming more common. These schemes provide more refined and consistent financial incentives to improve behaviour compared to fines.

2.1. Real-time and retrospective feedback

Intelligent Speed Adaptation (ISA) technology alerts drivers to their speeding behaviour in real time using audible tones, visual warnings on a screen and, in some cases, pushback on the throttle itself. The results of ISA trials allude to the possibility that real-time feedback may be sufficient to encourage a change in behaviour. For example, drivers in an ISA trial conducted in NSW, Australia revealed that being advised they were speeding (using an audible warning) increased their awareness of their frequency of speeding behaviour and made them aware they were speeding when they inadvertently drove in excess of the posted speed limit. Overall, 89% of vehicles recorded lower proportions of time speeding with an ISA device installed than before it was installed (NSW Centre for Road Safety, 2010). These results are consistent with other ISA trials (for example Jamson, 2006) although a study of young drivers has found that monitoring and alerts by themselves are not sufficient to change risky driving behaviour in the long term (Farmer et al., 2010). A small-scale study with 37 participants, incorporating a real-time feedback and reward scheme[2] for participants to reduce speeding, found that speeding was reduced during the feedback phase. After the completion of the feedback phase, drivers' speeding increased but remained lower than the baseline phase for higher speed limits[3]. The authors note that the speed limit was a significant factor in explaining behaviour (Merrikhpour et al., 2012; Merrikhpour, 2013). This suggests that a proportion of the benefits from feedback schemes are retained after feedback are no longer provided. In addition, the extent to which changes occur vary substantially by spatial characteristics and this should be taken into account when using these strategies. Bolderdijk et al. (2011) provided feedback to participants using a personalised website as part of a PAYD study and observed reductions in speeding during the intervention. The authors do not distinguish between the effects of the financial and awareness components of the study but note that few participants visited the website. This may partially explain why after the end of the intervention phase speeding increased relative to the baseline phase indicating that a financial incentive alone may not induce long term changes. It would appear that merely providing feedback is not sufficient and there needs to be either a compulsion or an incentive for drivers to access the feedback. This could simply be a matter of asking drivers to confirm whether they did or did not drive each day as a condition of receiving the financial incentive.

The effectiveness of feedback on other behaviours has also been studied. For instance, Donmez et al. (2008) used driving simulators to test the effect on braking behaviour of real-time and retrospective feedback presented at the end of each trip. The authors found that the results were similar for real-time feedback combined with retrospective feedback and retrospective feedback alone with both showing significant improvement compared to drivers that received no feedback. A learning effect was also observed whereby braking behaviour (for both feedback types) improved over the four simulated driving sessions. Trials in commercial vehicles resulted in similar improvements and significant reductions in crash rates (38%) after the feedback was introduced compared to the control group which received no feedback (19% reduction) (Toledo et al., 2008).

While most studies have found feedback to be effective in changing behaviour, there is some variation between different groups of drivers. A study on the effect of feedback on teenage drivers (Simons-Morton et al., 2013) found that it was necessary for parents to be informed of the behaviour. Feedback only seen by the drivers themselves was not effective at reducing risky driving behaviour, heavy braking and sharp turns in particular. These results are not universal with other studies finding young drivers to benefit from feedback (for example, Musicant and Lampel, 2010). The difference in results shares similarities with research on the influence of parents and peers on young drivers' behaviour. The research suggests that children's driving style is strongly correlated with that of their parents (Bianchi and Summala, 2004; Taubman - Ben-Ari et al., 2005; Prato et al., 2009) but the evidence also shows a relationship with the behaviour (and perceptions) of peers (Fleiter et al., 2006; Simons-Morton et al., 2012). Post-trip feedback with parental involvement may be related to the way in which the opinions and behaviour of passengers and other road users is prioritised over family members that are not present (Haglund and Åberg, 2000). In effect, the feedback mechanism may be creating a situation in which the parent becomes a 'phantom' passenger by virtue of being able to view the driver's behaviour. It is possible that

[1] Active ISA is also known as active accelerator pedal (AAP).

[2] The reward scheme consisted of points accumulated for compliance which could be redeemed for gift cards at the completion of the study.

[3] The authors defined higher speed limits as 70, 80, 90 and 100 km/h speed limits.

by providing personalised feedback, drivers' mental models are being developed by making them aware of manoeuvres that either they are doing themselves or other drivers are doing. The feedback may be functioning as some form of assisted training to accelerate some of the benefits that arise from experience (Underwood, 2007). This may explain why the studies of feedback with young drivers show quite different results to those for more experienced drivers.

There is also evidence of the benefits of feedback from research on speed display signs (Lee et al., 2006; Gehlert et al., 2012), however, there is some question as to how much this is due to increased awareness of speeding or if the presence of the signs imply greater enforcement and, therefore, a higher likelihood of being fined. In this case, the immediate threat of a fine may be acting as motivation towards changing the driving speed at that particular point in time. This would be consistent with research on informational interventions in which it was found that education improves the likelihood of those that were already concerned about the issue at hand but not for others (Bolderdijk et al., 2013) and financial costs are one source of motivation as is conforming with social norms (Schultz, 2010). Taking these aspects together it appears that to gain the most benefit from a behaviour change scheme involving feedback, it is necessary to couple the feedback with motivation of some sort, either existing or activated through financial costs, incentives or adherence to community norms (Schultz, 2010). There is also some evidence that advanced driver assistance systems (ADAS) have a beneficial impact on reducing crash risk. Benmimoun et al. (2011) describe an effort to compute changes in risk from detecting near crash events before and after the activation of an ADAS technology using data collected from 1000 vehicles. The final findings (Kessler et al., 2012) show a reduction in predicted crashes (and therefore crash risk) with these systems with differences between motorways, rural areas and urban areas although the authors identify that there are some interactions when more than one system (such as cruise control and speed limiting) are in use at the same time.

2.2. Financial incentives

Financial incentives have been used to encourage drivers to comply with speed limits and other road rules with legislated fines for speeding infringement being the most common form. Some insurance companies have trialled PAYD insurance schemes typically targeted at young drivers that pay the highest premiums (for example, The Co-operative Insurance, 2012; Desyllas and Sako, 2012). Co-operative Insurance (United Kingdom) claims that 51% of drivers under 25 would save money under their insurance plan (The Co-operative Insurance, 2012) although that leaves the remainder potentially paying more. The benefit of this compared to fines is that the monetary component is linked to all driving behaviour and not only the (rare) occasions when a driver is caught speeding by police or speed cameras.

Hultkrantz and Lindberg (2009) conducted an on-road experiment with 114 cars with ISA devices installed[4]. Drivers were provided with a monthly monetary incentive (250 SEK or 500 SEK) for each of the two months of the study with this incentive being reduced by 0.10–1 SEK or by 0.10–2 SEK (depending on the magnitude and the group) for each minute driven over the speed limit for some of the participants. Drivers were informed of their remaining incentive at the end of each month. The findings were that there was no significant difference in changes in speeding behaviour in the first month between those with a variable and fixed incentive. However, in the second month, drivers that received a variable incentive reduced their speeding behaviour by 64% compared to 15% for those receiving a fixed incentive. There was also no difference in behaviour for the drivers with higher penalty rates compared to drivers with lower penalty rates. The authors suggest that drivers decide whether or not to reduce their speeding behaviour and this appears to be unrelated to the amount of the incentive.

Other notable PAYD studies include an eight month study conducted in The Netherlands (Bolderdijk et al., 2011) and a Danish ISA trial that incorporated PAYD principles (Lahrmann et al., 2012). Bolderdijk et al. (2011) found a small drop in speeding behaviour (from 18.6% of the distance to 17.6%), however this increased to 20.5% once the intervention was withdrawn. A control group exhibited increases from 17.9% to 19.7% over the same period. The authors suggest that the increases for both groups may be attributable to seasonal differences or a reduced awareness of the monitoring process. Elvik (2014) summarised the results of seven PAYD studies, including the Swedish and Dutch studies mentioned earlier. Elvik (2014) states that while it is difficult to compare the results due to different methodologies and interventions, all were successful at promoting speeding reductions but that self-selection bias and high dropout rates suggest that the worst drivers are more reluctant to change.

Table 1
Age and gender characteristics of final sample (Greaves et al., 2013).

	Age group		
Num. drivers	17–30	31–45	46–65
Gender			
Male	5	19	20
Female	21	24	17

3. Intervention and data collection

The literature suggests that both feedback and financial incentives can reduce risky driving behaviour, including speeding. In this paper, data from a PAYD study conducted in Sydney, Australia with 148 drivers (see Greaves et al., 2010 for more information on the design of the overall study) were used. Although the aim was to recruit an equal number of male and female drivers in two age groups (17–30 and 31–65), young male drivers proved to be particularly difficult to recruit. The small number of young male drivers means that the results for male drivers are skewed towards older drivers. Of the 148 drivers, 133 completed all phases of the study and after excluding participants with inconsistent GPS and odometer readings and those with long holidays or other lifestyle changes, 106 eligible drivers remained. The demographic characteristics of the final 106 drivers are shown in Table 1.

Driving data were collected using in-vehicle GPS devices that recorded latitude, longitude and speed among other variables each second. This was then matched to a road network to identify the appropriate speed limit for each observation. Subsequently, additional spatial and temporal characteristics were added to each observation as discussed in Ellison et al. (2013). The unprocessed GPS data contained over 80 million observations representing more than 22,000 h of driving. Taken together with the supplementary spatial and temporal datasets, the data employed in this research totalled 30 GB (Gigabytes) of storage space and had to be used in a relational database to make it manageable.

The data were collected in two phases, an initial five-week *before* phase followed by a five-week *after* phase following the introduction of the intervention. During the *before* phase,

[4] These participants had already been using the ISA devices with feedback provided but no monetary incentive.

Table 2
Per kilometre rates (in AUD) used in the after phase (Greaves and Fifer, 2010).

	Time of day and speeding status			
	Day (non-speeding)	Day (speeding)	Night (non-speeding)	Night (speeding)
Age				
17–30	$0.20	$0.60	$0.80	$2.40
31–65	$0.15	$0.45	$0.60	$1.20

participants were not informed of the purpose of the study, or that their speeding behaviour was being monitored to avoid influencing results. Participants were informed of the purpose of the study when the intervention was introduced, with the option to withdraw from the study, but nobody selected this option. This procedure was approved by the University Human Research Ethics Committee. For similar reasons, the five-week *before* phase started at least one week after the installation of the GPS devices to reduce any potential 'halo' effects, that is artificial changes in behaviour resulting from awareness of being monitored (Stopher et al., 2007).

The driving in the *before* phase was used to calculate the (theoretical) charges that would have been levied based on the vehicle kilometres travelled (VKT), night time driving and speeding charges shown in Table 2. This was then used as the starting incentive for each driver such that if a driver drove identically in the *after* phase they would end the study with no remaining incentive. If a driver improved, by reducing the combination of VKT, night time VKT and speeding, then they would receive what remained of the incentive amount. For example, one participant received a starting incentive of $510 based on his driving in the *before* phase. In the *after* phase the participant reduced VKT from 1727 km to 1631 km, speeding from 12% to 5% and increased night time driving from 23% to 29% resulting in a final charge of $480 or a remaining incentive of $30. On average, VKT reduced by 9.8%, distance speeding reduced by 8.6% and night-time driving increased by 1% (Greaves et al., 2013).

Throughout the study, participants were asked to access an online prompted recall website, shown in Fig. 1, where they were shown their trips and asked to fill in additional information on who was driving, the number of passengers, the purpose of the trip and if there were any intermediate stops. For the purposes of the analysis presented here, only information for the primary driver were used with other trip details used as explanatory variables. A similar interface, shown in Fig. 2, was used in the after phase of the study to collect the same information and to display speeding behaviour (for each trip) and the remaining incentive.

Although it is not possible to determine how participants looked at and interpreted the information, the number of website logins was used as a proxy for exposure to the information (frequency of speeding, remaining incentive) provided.

4. Methodology

The aim here was to determine the extent to which the intervention of the PAYD study resulted in changes to the risk of involvement in a casualty crash. To achieve this, a number of steps were required. Firstly, the data needed to be processed in such a way that the influence of the driver could be isolated. This is discussed in Section 4.1. Second, it was necessary to devise a way to separate the effect of the financial and awareness components of the intervention (see Section 4.2). Lastly, multilevel risk models were developed to evaluate the changes to driver behaviour that occurred as a result of the intervention. The model development is described in Section 4.3.

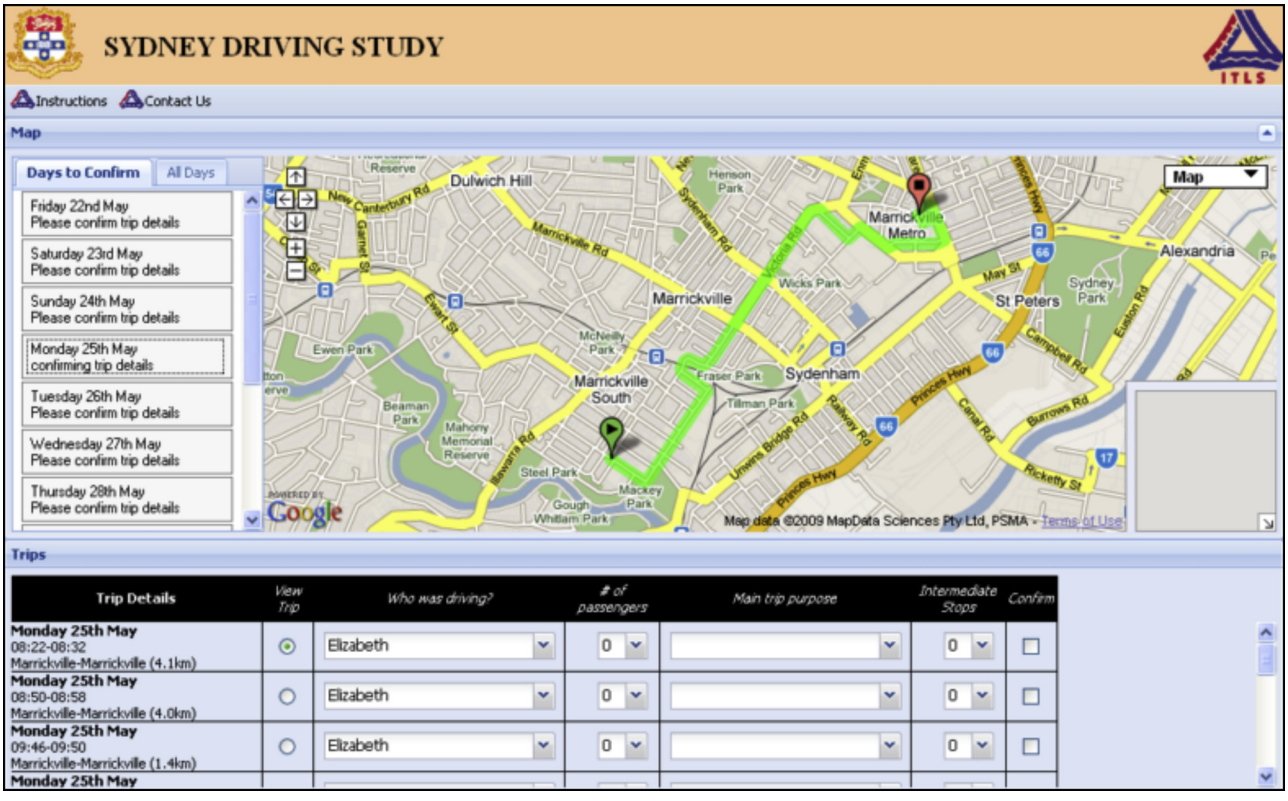

Fig. 1. Screenshot of prompted recall website during baseline phase (Greaves et al., 2010).

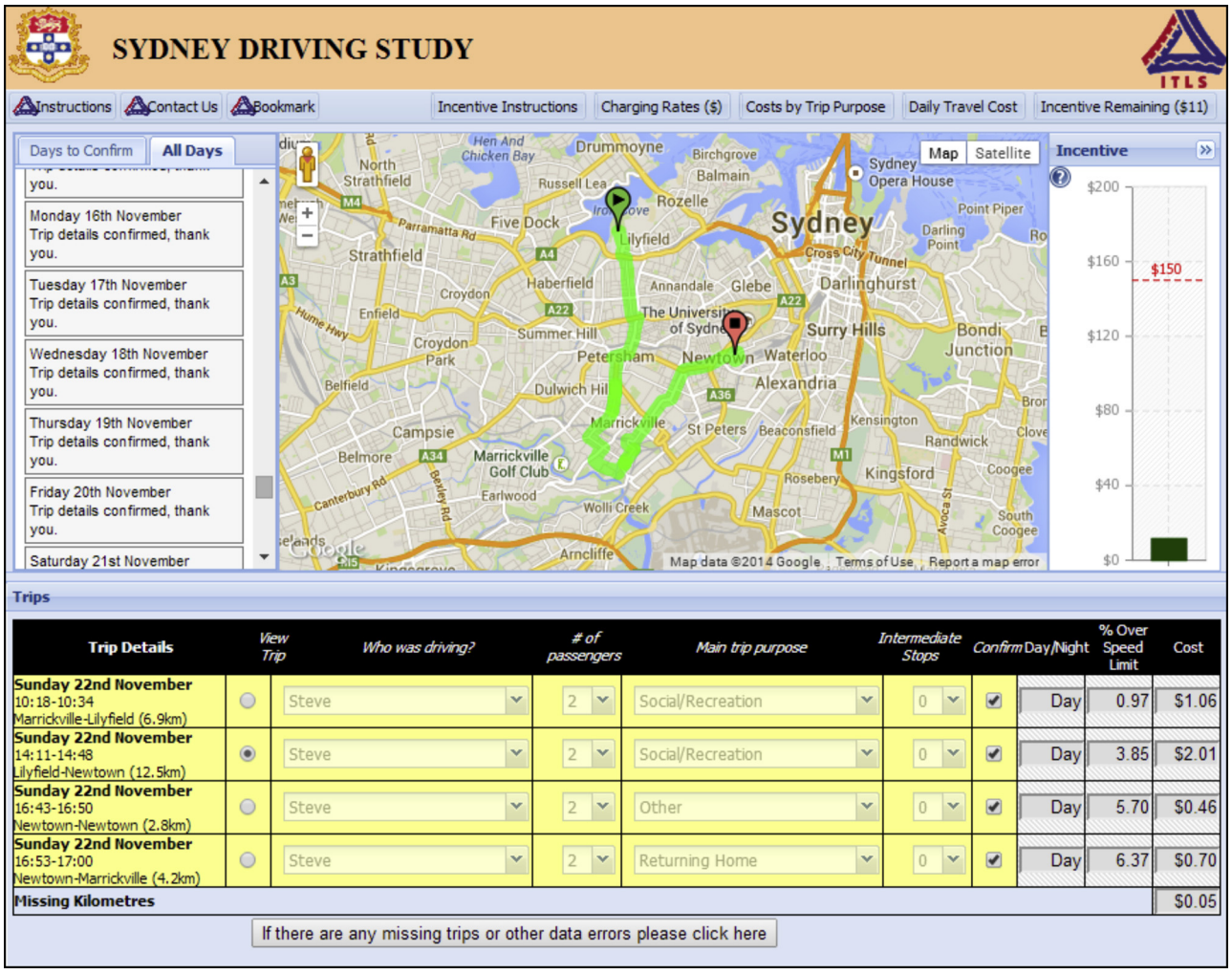

Fig. 2. Screenshot of prompted recall website during charging (after) phase.

4.1. Data processing

Since the data were collected during day-to-day driving, over time, it was necessary to control for exogenous factors such as the road environment. This was done by applying Temporal and Spatial Identifiers (TSIs) (described in detail in Ellison et al., 2013), which represent the spatiotemporal characteristics associated with each observation using codes for each characteristics that applies, and then aggregating the data by road segment. A new road segment started at the beginning of each trip and every time the TSI changed. In the example illustrated in Fig. 3, segment 1 is a 60 km/h zone near a signalised intersection. Segment 2 starts when the speed limit changes to 40 km/h, the school zone starts and the vehicle is no longer near an intersection. Both segments occur on a weekday morning, during a commute to work with no passengers. After excluding data from secondary drivers, the final dataset contained 1.98 million road segments covering 199,904 km of driving (VKT).

To provide a common unit of comparison of risk and taking into account varying magnitudes, distances and environments

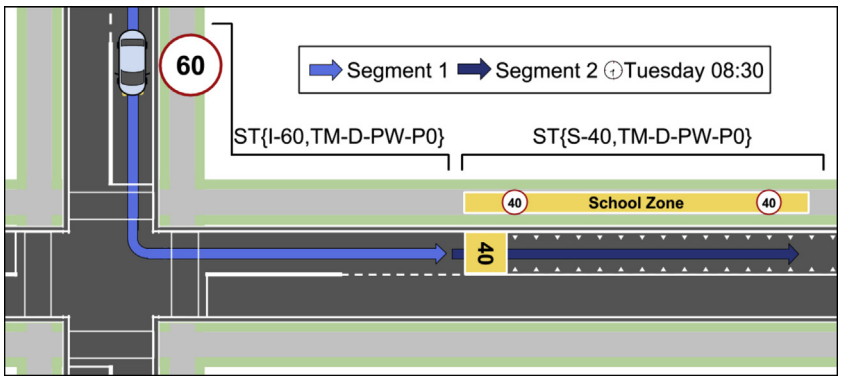

Fig. 3. Example of Temporal and Spatial Identifiers.

driven, Driver Behaviour Profiles (DBPs) (developed in Ellison, 2014) were used. DBPs are common risk scores, derived from GPS data, spatiotemporal data and risk curves for speeding, acceleration and braking behaviour. Starting with disaggregate (second-by-second) GPS data, a relative risk of involvement in a casualty crash is calculated for each observation using the relative risk curves found by (for speeding) Kloeden et al. (1997). The same is done for acceleration and braking magnitudes observed for each second of driving. These are then aggregated into road segments delineated by TSI as shown in Fig. 3 to control for the spatiotemporal environment before being normalised to fit on a common 0 (low risk) to 100 (high risk) scale.These relative risks are then converted into three individual risk scores for speeding, acceleration and braking taking into account the contribution of each TSI. A composite risk score is then determined by weighting each behavioural risk score by its contribution to the risk of a casualty crash. Ultimately, the risk scores represent the relative risk of involvement in a casualty crash such that a driver with a score of 30 has twice the (relative) risk of a driver with a score of 15.

The advantage of this approach is that direct comparisons can be made of the risks associated with driving between different drivers, time periods and spatiotemporal environments. While a control group can control for exogenous changes that affect all participants, this approach recognises both inherent variability in driver behaviour and localised changes such as temporary construction work that may change where and when individual participants drive. These procedures were run independently for each of the three distinct phases of the study (shown in Fig. 4), where the first phase consists of the *before* phase, the second phase consists of the part of the *after* phase (which we call *after one*) in which the driver could still save money, and a third phase that consists of the remainder of the *after* phase (which we refer to as *after two*) in which the driver no longer has a remaining financial incentive. Using the same example participant as used earlier, the total score was 41 in the *before* phase and 26 in the *after one* phase representing a reduction in the risk of involvement in a casualty crash of 37%.

4.2. Study phases

During the *before* (or baseline) phase drivers were shown where they went but not any information about their speeding, acceleration and braking behaviour (see Fig. 1). Prior to the start of the charging (*after*) phase, drivers were shown their speeding behaviour for each trip as a proportion of the distance travelled and a monetary incentive calculated based on their driving in the before phase as shown in Fig. 2. During the *after one* phase every kilometre driven reduced the monetary incentive by the amounts in Table 2. Drivers that did not reduce their VKT, speeding and night time driving, compared to their respective before phase, saw their financial incentive gradually reduce to zero. From that point until the completion of the study (*after two* phase), these drivers were still made aware of their speeding behaviour but the financial component of the study no longer applied.

It was suspected that the financial incentive ceased to be a motivator to change behaviour when it reached an unknown amount that was low, but higher than zero. At that point the remaining incentive was no longer of sufficient perceived value to the participant to encourage change. To isolate the effect of the financial intervention it was necessary to identify the point at which this occurred. To accomplish this, risk scores were generated using data where the remaining incentive was 0, 5, 10 and 15 dollars and similarly a threshold of 0, 5, 10 and 15% of the original incentive amount given that the starting incentive varied from driver-to-driver based on their behaviour in the before phase. ANOVA analyses were used to test for statistically significant differences in speeding risk scores for each threshold and through this process a 5% threshold was deemed to be most appropriate. As such, the *after one* phase comprised of driving with a remaining incentive greater than 5% of the starting incentive and the *after two* phase comprised of driving with a remaining incentive of 5% or lower.

Table 3
Multilevel regression model independent variables.

Variable	Level	Description
Spatial		
Speed limit	TSI	**40**, 50, 60, 70, 80, 90, 100, 110 (km/h)
School zone	TSI	**0: No**, 1: Yes
Rain	TSI	**0: No**, 1: Yes
Temporal		
Time of day	TSI	**1: Morning**, 2: Day 3: Afternoon, 4: Night
Weekend	TSI	**0: No**, 1: Yes
Number of passengers	TSI	**0: None**, 1: 1, 2: 2, 3: 3+
Vehicle characteristics		
Vehicle transmission	Driver	1: Automatic, 2: Manual
Vehicle body	Driver	**1: Sedan**, 2: Hatchback, 3: Other
Vehicle model year	Driver	**1: ≤1999**, 2: 2000–2004, 3: 2005 or newer (year)
Driver demographics		
Gender	Driver	**1: Male**, 2: Female
Age	Driver	**1: 18–30**, 2: 31–45, 3: 46–65 (years)
Study components		
Made money	Study phase	**1: Yes**, 2: No
Starting incentive	Study phase	Starting incentive in dollars
Phase	Study phase	**1: Before**, 2: After, 3: After 2
Logins	Study phase	Absolute number of logins

Note: bolded values refer to the regression reference categories and units are shown in brackets.

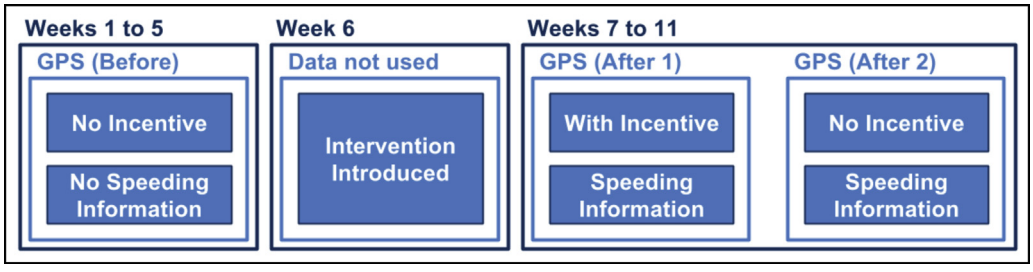

Fig. 4. Study phases.

4.3. Multilevel risk models

To determine if providing drivers with information on their speeding behaviour would induce a change in behaviour, a multilevel risk model was developed. Multilevel models are regression models that take into account the hierarchical relationships between observations, that is to say they recognise that the observations are not entirely independent of each other. The structure of the model is defined by the analyst and can take several forms. Although a number of different structures were attempted, the final model comprises three hierarchical levels. The highest level is the TSI level representing the spatiotemporal environment, the second is the driver level incorporating driver and vehicle characteristics and the third level is the study phase level. The hierarchical structure of these models ensures that changes in behaviour are compared like-for-like with driving in each phase associated with a particular driver and a particular TSI. This controls for any differences between the different study phases in where and when participants drive. This is an important difference with previous PAYD studies in which the before and after phases are often not comparable due to the influence of conflating factors.

Separate models were developed for each of the four behavioural risk scores which form a DBP: speeding, acceleration, braking and a composite or total risk score. These risk scores were used as the dependant variable in each of their respective models. It should be noted at this point that although changes in acceleration and braking behaviour were analysed, at no point in the study were participants made aware that their acceleration and braking behaviour were being monitored. This is distinct from speeding behaviour which was revealed to participants as part of the intervention. In contrast, while VKT and night-time driving were specifically targeted by the intervention, their effects are controlled for using TSIs in this analysis.

The independent variables were kept the same for each of the models to ease comparison. They are summarised in Table 3 along with the level each belongs to and its composition. Since many variables are categorical, both parametric and non-parametric models were run with little difference between them. The non-parametric models are shown here because they are simpler to interpret.

In addition to the TSI and driver-level variables, a number of variables were used to account for the speeding awareness and financial aspects of the study that applied in the after phase. These

Table 4
Parameter estimates for before-and-after multilevel risk models.

	Speeding			Acceleration			Braking			Total		
	B	Std. Err.	Sig.	B	Std. Err.	Sig.	B	Std. Err.	Sig.	B	Std. Err.	Sig.
Intercept	3.457	0.184	0.000	0.805	0.272	0.003	2.687	0.186	0.000	4.058	0.084	0.000
TSI Level												
Speed limit (50)	-0.455	0.148	0.002	1.773	0.198	0.000	1.210	0.138	0.000	-0.110	0.059	0.060
Speed Limit (60)	-1.048	0.148	0.000	1.493	0.197	0.000	1.283	0.137	0.000	-0.298	0.058	0.000
Speed Limit (70)	-1.709	0.151	0.000	0.523	0.202	0.009	0.661	0.139	0.000	-0.785	0.060	0.000
Speed Limit (80)	-1.887	0.154	0.000	-0.361	0.208	0.083	-0.119	0.143	0.404	-1.159	0.062	0.000
Speed Limit (90)	-2.255	0.161	0.000	-3.048	0.242	0.000	-1.552	0.152	0.000	-2.122	0.068	0.000
Speed Limit (100)	-1.989	0.176	0.000	-4.078	0.332	0.000	-3.323	0.195	0.000	-2.372	0.082	0.000
Speed Limit (110)	-2.590	0.191	0.000	-4.313	0.401	0.000	-3.137	0.212	0.000	-2.677	0.093	0.000
School Zone	-0.443	0.199	0.026	0.244	0.312	0.434	0.757	0.221	0.001	-0.112	0.090	0.214
Rain	-0.714	0.093	0.000	-1.686	0.159	0.000	-0.899	0.106	0.000	-0.358	0.048	0.000
Time (Day)	0.213	0.065	0.001	0.710	0.109	0.000	0.239	0.075	0.001	0.067	0.034	0.047
Time (Afternoon)	0.040	0.064	0.537	0.659	0.108	0.000	0.292	0.074	0.000	0.017	0.034	0.621
Time (Night)	-0.137	0.073	0.062	-0.357	0.124	0.004	-0.527	0.084	0.000	-0.307	0.039	0.000
Weekend	0.206	0.043	0.000	-0.688	0.072	0.000	-0.347	0.049	0.000	-0.033	0.023	0.144
Num. Passengers	-0.070	0.021	0.001	-0.161	0.035	0.000	-0.083	0.024	0.001	-0.043	0.011	0.000
Driver Level												
Type (Hatchback)	-0.340	0.053	0.000	-0.188	0.088	0.033	-0.046	0.060	0.439	-0.171	0.028	0.000
Type (Other)	0.071	0.053	0.180	-0.210	0.089	0.019	-0.148	0.061	0.015	-0.059	0.028	0.035
Model Year	0.179	0.028	0.000	0.044	0.048	0.351	-0.046	0.032	0.151	0.040	0.015	0.007
Transmission (Manual)	-0.299	0.051	0.000	-0.100	0.084	0.231	-0.150	0.057	0.008	-0.119	0.027	0.000
Male : Age	-0.209	0.029	0.000	-0.128	0.048	0.007	-0.150	0.033	0.000	-0.121	0.015	0.000
Female : Age	-0.153	0.034	0.000	-0.127	0.056	0.024	-0.147	0.038	0.000	-0.101	0.018	0.000
Phase / Intervention Level												
Made Money	-0.162	0.055	0.003	0.156	0.083	0.059	0.160	0.059	0.007	0.000	0.032	0.998
Starting Incentive	0.014	0.001	0.000	0.014	0.002	0.000	0.004	0.001	0.001	0.006	0.001	0.000
Phase (After 1)	-0.346	0.014	0.000	-0.075	0.014	0.000	-0.150	0.013	0.000	-0.133	0.010	0.000
Phase (After 2)	-0.307	0.023	0.000	-0.274	0.025	0.000	-0.247	0.023	0.000	-0.201	0.018	0.000
Drivers who did not make money in the study												
Before : Logins	0.007	0.002	0.000	0.013	0.002	0.000	0.004	0.002	0.011	0.005	0.001	0.000
After 1 : Logins	-0.005	0.001	0.001	0.010	0.002	0.000	0.009	0.001	0.000	-0.001	0.001	0.488
After 2 : Logins	0.001	0.002	0.460	0.011	0.002	0.000	0.005	0.002	0.001	0.003	0.001	0.012
Drivers who did make money in the study												
Before : Logins	-0.010	0.002	0.000	-0.015	0.002	0.000	-0.005	0.001	0.001	-0.005	0.001	0.000
After 1 : Logins	-0.029	0.002	0.000	-0.011	0.001	0.000	-0.002	0.001	0.150	-0.012	0.001	0.000
After 2 : Logins	Not Applicable											

Statistically significant increase at the $p = .05$ level
Statistically significant reduction at the $p = .05$ level

included a variable to indicate if the participant had some remaining financial incentive at the completion of the study, the starting incentive, the number of days in the before phase on which the study website was accessed and the number of days on which the study website was accessed in each phase. Importantly, the *made money* variable that indicates if the driver received money at the completion of the study due to reducing the combination of VKT, night-time driving and speeding (as per the PAYD scheme) was applied to observations for all phases of the study. The same was true for the starting incentive. This accounts for any inherent driver characteristics that would have made the participant more or less likely to change their behaviour.

5. Results

The parameter estimates are shown in Table 4. The model fit was good with the predicted values being consistent with the observed values as illustrated in Fig. 5. In addition, most parameter estimates were sufficiently reliable (as judged by their standard errors) and the statistically significant spatiotemporal and driver characteristics were consistent with multilevel models derived using data only from the before phase. This provides some evidence that the TSI approach works well at controlling for differences in the frequency of different spatiotemporal environments in each of the study phases.

In terms of the parameter estimates themselves, shown in Table 4, the significance and direction of the TSI-level and driver-level variables were consistent with prior research and *a priori* expectations. Namely, the spatiotemporal (TSI) variables were the strongest predictors with lower speeding risk scores (reflecting lower risks) associated with school zones, rain, weekdays and a greater number of passengers. Older drivers generally exhibited lower speeding risk scores relative to younger drivers of the same gender, with the effect more pronounced for male drivers reflecting higher speeding risk scores for younger male drivers. Some vehicle characteristics were also important with newer cars and automatic transmissions associated with higher speeding risk scores.

The modelling results (shown in Table 4 under the *phase/intervention* heading) strongly suggest that the intervention was successful in reducing speeding risk scores, and by extension, the risks of involvement in a casualty crash. This was the case for both the financial scheme (the monetary incentive) and making drivers aware of their speeding behaviour. Unsurprisingly given that the frequency of speeding formed a part of the charging regime, drivers that earned money at the end of the study exhibited lower speeding risk scores. Although it was possible to receive an incentive by reducing VKT and not speeding, speeding appeared to be the easiest aspect to change since it required no changes to when and how much participants drove. Drivers with greater starting incentives, again unsurprisingly, exhibited higher speeding risk scores which is reflective of (in most cases) more frequent speeding in the *before* phase which was used to calculate the starting incentive. Nonetheless, drivers with higher frequencies of speeding in the *before* phase could have made large reductions in speeding behaviour and yet still engaged in more frequent speeding than other drivers.

Arguably of more interest is how speeding behaviour is associated with the number of website logins in each of the study

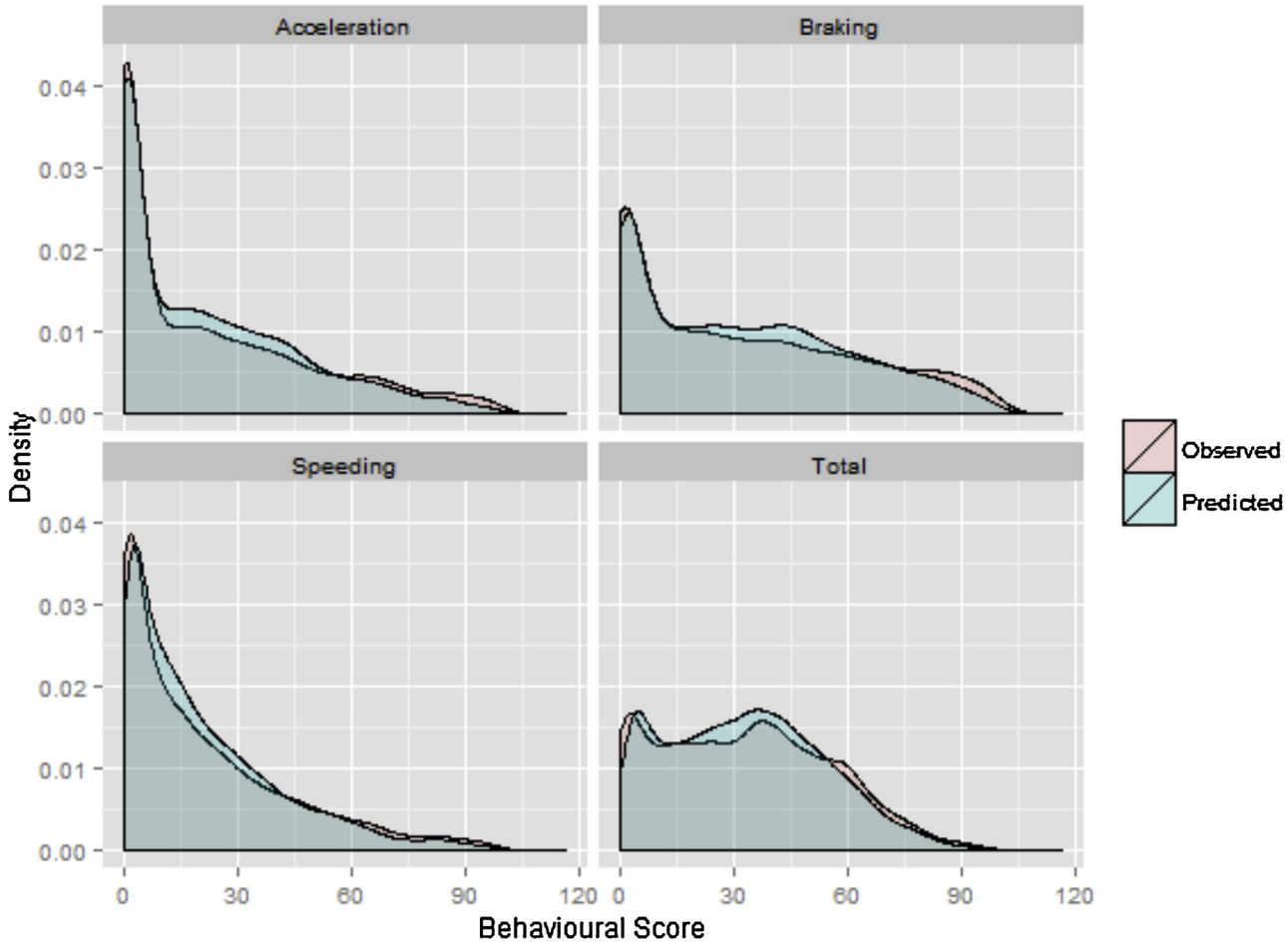

Fig. 5. Distribution of observed and predicted values for all study phases.

phases. Importantly, although the number of website logins was used as a proxy for speeding awareness in the *after* phase, in the *before* phase participants were not shown any information about their trips other than where and when they drove (refer to Fig. 1).

Since drivers that made money improved their behaviour in some way (by reducing the combination of VKT, night time driving and speeding) and those that did not make money did not, an interaction effect was used to divide these two categories of participants. For those drivers that did not make money, each additional website login is associated with higher speeding risk scores in the before phase ($p = .000$, $B = .007$). It is uncertain why this is the case but may be due to drivers with more trips accessing the website frequently to keep their trip details up-to-date. During the *after one* phase, these same drivers exhibited lower speeding risk scores ($p = .001$, $B = -0.005$) as the frequency of logins increased. Once the financial component was removed, in the *after two* phase, there was no statistically significant relationship between the frequency of logins and the speeding risk score. Taken together with the strong negative relationship between the *after two* phase[5] and speeding risk scores relative to the *before* phase, this suggests that for this group of drivers once the financial incentive was removed, additional exposure to feedback on their speeding behaviour made no difference to speeding behaviour. However, speeding remained significantly less likely than in the *before* phase and only marginally less than in the *after one* phase for all drivers, including those that did make money in the study.

For those drivers that did make money, there was a negative relationship between the frequency of logins and the speeding risk score in the before phase ($p = .000$, $B = -0.010$), which is the opposite effect of those that did not make money. It is possible that these drivers were more conscientious drivers to begin with as this would be consistent with making a greater effort to reduce their VKT and speeding behaviour after being introduced to the intervention. In keeping with this lower speeding risk scores were associated with more frequent website logins ($p = .000$, $B = -0.029$). The magnitude of the relationship was three times stronger in the *after one* phase than in the *before* phase demonstrating that increased exposure to the intervention resulted in incremental benefits to reducing speeding behaviour.

The relationship between the study phase and the speeding risk score was also highly significant ($p = .000$, $B = -0.346$) with the *after one* phase exhibiting a negative effect on speeding risk scores and the *after two* phase exhibiting a significant negative effect but of a (12%) lower magnitude than the *after one* phase. However, it should be noted that only participants that did not make money were included in the *after two* phase.

Acceleration, braking and (by extension) total risk scores largely followed a similar pattern to speeding behaviour with the *after* phase exhibiting significantly lower risk scores than in the *before* phase. However, unlike with speeding these effects were stronger in the *after two* phase than in the *after one* phase. It is not clear why this is the case but is observed in all of these models. The main exception to this is in braking behaviour in certain situations (particularly slower speed limits and school zones) and for drivers that did not make money in the study. This may be because abiding by the speed limit sometimes requires more frequent braking behaviour somewhat increasing the risks associated with heavy braking. Since participants were never explicitly shown or told that their acceleration and braking behaviour was monitored, changes in these risk scores cannot be directly attributable to the financial incentive or the speeding information. It is possible, given that similar trends are observed in relation to participants' use of the study website, that these results are reflective of more conscientious driving by participants as a by-product of becoming more self-aware of their own behaviour.

These results suggest that providing a financial incentive and increasing drivers' awareness of their own speeding behaviour has a measurable effect on reducing speeding behaviour with incremental benefits the more frequently drivers are exposed to information about the frequency of their speeding behaviour. Furthermore, it appears that when the financial incentive is removed (*after two* phase) speeding remains substantially reduced from the before phase, albeit to a slightly lesser extent than when the financial incentive is in place (after one). Although the *after two* phase of the study only observes drivers over the short term it provides some indication that improving drivers' awareness of their own speeding behaviour can induce beneficial changes in drivers' speeding behaviour independently of a financial incentive. This is illustrated in Fig. 6 where the majority of observations in both after phases are found in the area shaded in green which represent driver-level speeding risk scores with lower speeding risk scores relative to the *before* phase. Furthermore, drivers with a higher number of website logins in the *after* phase, shown with larger points, generally exhibit smaller differences between the two *after* phases suggesting that more frequent feedback is likely to create the conditions for longer term changes, perhaps provided through an in-vehicle display. In fact, there were a small but significant number of participants exhibiting lower speeding risk scores in the *after two* phase than in the *after one* phase, seen in Fig. 6 where the *after two* (orange) risk score is to the left of the *after one* (blue) risk score.

There is evidently a distinct difference in drivers' behaviour between the different phases of the study which strongly suggests that there is a statistically significant relationship between drivers' awareness of their speeding behaviour and their speeding behaviour. This appears to be reinforced by the financial incentive, perhaps as an initial motivator to change speeding behaviour. More broadly – although the reasons are unclear – there appears to be a beneficial 'halo' effect on other forms of driver behaviour despite only speeding being specifically targeted by the intervention.

6. Discussion

The results show that a financial incentive and making drivers aware of their speeding through personalised feedback are effective at encouraging drivers to reduce their speeding behaviour relative to the *before* phase. Comparing the effect of the study phases, speeding risk scores were measurably lower in the *after one* phase (when both financial and awareness components were in effect) compared to the before phase. Speeding risk scores in the *after two* phase, when the financial incentive was no longer applicable, were 12–14% higher than in the *after one* phase. This was still substantially lower than in the *before* phase and even more so given that only drivers that did not make money were included in the *after two* phase. This suggests that making drivers aware of their speeding behaviour – or simply that their speeding behaviour is being monitored – is sufficient to reduce the speeding behaviour of most drivers, at least in the short term, irrespective of a financial incentive, although the financial incentive appears to act as an additional motivator.

In addition, the results show that (in general) the higher the starting incentive the higher the speeding risk score and the smaller the improvement in speeding behaviour in the *after* phase. Since the starting incentive was partially determined by the frequency of speeding in the *before* phase this suggests that the worst speeders also exhibited the smallest magnitude changes in behaviour relative to their own *before* phase speeding behaviour. This is despite these drivers having the greatest possible absolute

[5] The after two phase only contained observations for drivers that did not make money in the study.

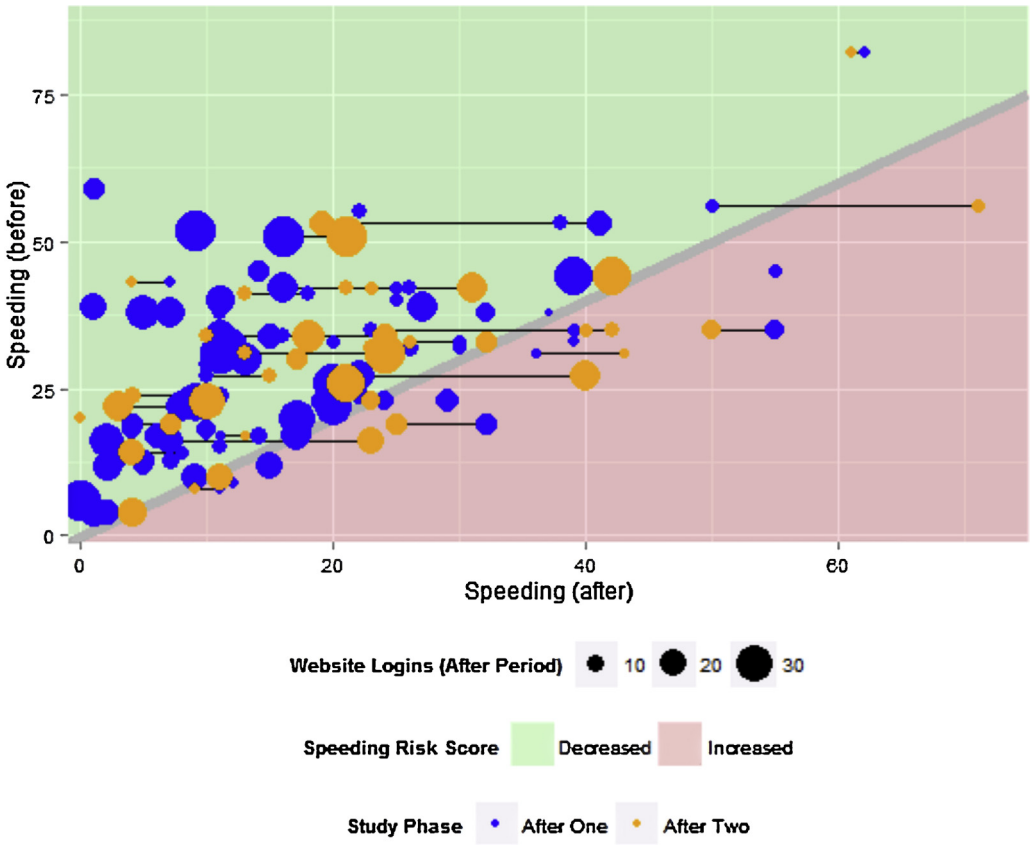

Fig. 6. Speeding behaviour between before and after phases (driver-level). (For interpretation of the references to colour in text, the reader is referred to the web version of this article.)

change given their higher risk scores in the baseline phase. Therefore, while the strategies result in significant reductions in aggregate speeding behaviour, these changes are disproportionately due to improvements in behaviour by drivers that were already (relatively) safer drivers. In effect, the drivers that need to change most – and at which many of the policies against speeding are targeted – are also the drivers that are least inclined to change their behaviour. This is reinforced by looking at the parameter estimates for the interaction between drivers that made money in the study and the number of logins to the study website.

In the before phase, during which time the interventions had not been introduced and drivers' had not been told that their speeding behaviour was being monitored, drivers that went on to make money in the *after* phase already exhibited a negative trend in speeding behaviour for every additional time they accessed the website. Those drivers that did not make money had the opposite effect. In the *after one* phase, both groups exhibited negative relationships but the magnitude was almost six times higher for the group that made money in the study. In the *after two* phase there was no statistically significant effect for those drivers who did not make money. These trends suggest that those drivers that made money in the study were already predisposed to being better drivers as judged by their conscientiousness in accessing the prompted-recall component of the study before the introduction of the intervention. A model similar to the model discussed in this paper was performed to examine the relative difference in absolute risk scores between drivers that made money and those that did not in each of the study phases. The results confirm that those drivers that made money in the study already exhibited lower speeding risk scores in the before phase with the magnitude difference in speeding risk scores between the two groups increasing seven-fold in the *after one* period.

Overall, although a small number of drivers appear entirely unwilling to change, the distribution of speeding risk scores, shown in Fig. 7, exhibit a clear shift to the left representing lower scores and therefore lower risk of a casualty crash in the *after one* phase relative to the before phase. In the *after two* phase, behaviour reverts some way back to the baseline behaviour, observed as a shift to the right, but a substantial difference still remains relative to the *before* phase.

What has been observed here is that the combination of a financial incentive and increasing awareness of a driver's own behaviour provides the best results across the sample. Increasing drivers' awareness of their behaviour is effective in reducing

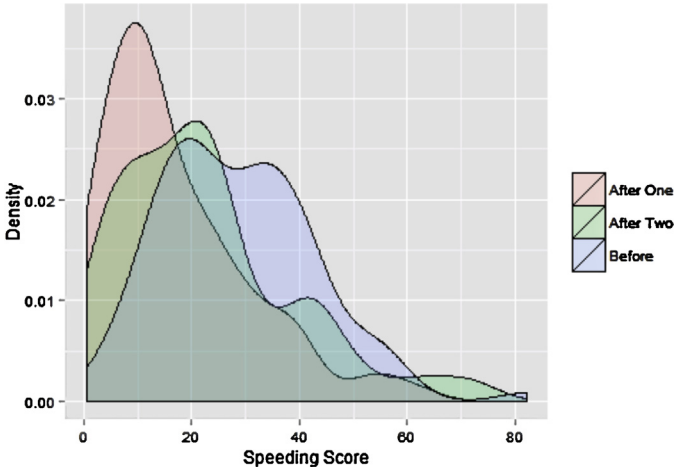

Fig. 7. Density of driver-level speeding scores in each study phase.

speeding behaviour independently, which is consistent with previous research (Merrikhpour et al., 2012) but the benefits of the financial incentive should not be discounted. Financial interventions by themselves have previously been shown to be effective (see Elvik, 2014 for a summary) but, to the authors' knowledge, prior to this paper there has not been an attempt to isolate the contribution of awareness and financial incentives for the same drivers within the same study. One PAYD study (Bolderdijk et al., 2011) incorporated both measures but only a small number of participants accessed the retrospective feedback making such an analysis impossible. The major distinction between the analysis presented here and prior research using data from PAYD and ISA trials is the measure of speeding behaviour is not the frequency of speeding *per se* but the risks associated with speeding (as well as acceleration and braking) behaviour. This accounts for the non-linear increase in risk for higher magnitudes while frequency on its own does not.

7. Conclusions

This study examines the effectiveness of a financial incentive and increasing speeding awareness as a means towards reducing the risks of involvement in a casualty crash faced by road users. Towards this end, there appears to be potential to improve driver behaviour through wider scale implementation of the strategies in this paper. For example, in-vehicle and road-side systems could be used to provide personalised feedback to drivers to make them more aware of their own behaviour. These systems could be built into new vehicles, purchased by individuals or could be provided in conjunction with insurance companies as part of pay-as-you-drive (PAYD) insurance plans. In most cases participation in these schemes would be voluntary but, potentially, legislation could be changed to require repeat speeding offenders to have an ISA device installed or to use a PAYD insurance plan as a condition for avoiding a license suspension.

It is important to note that the largest reductions in speeding behaviour were observed when drivers were also provided with a financial incentive to reduce their speeding behaviour. For policy makers this suggests that financial incentives could be devised to reduce speeding behaviour among a large proportion of drivers. This must be done on a more frequent and systematic basis than currently done through speeding fines given that the participants in this study were still liable for speeding fines through the usual enforcement mechanisms during the study. This could be applied through insurance companies running in-vehicle monitoring devices as part of PAYD insurance plans, which would work well in conjunction with the possibilities for increasing awareness. An additional option would be for governments to charge higher annual registration fees with either refunds or discounts off the annual renewal cost for drivers or vehicles that have not been recorded or caught speeding. This would need to be done in conjunction with enforcement and a greater number of speed cameras, including point-to-point speed cameras. In jurisdictions with high thresholds for speed fines – such as Norway where fines are not routinely issued for speeding by less than 6 km/h (Elvik, 2012) – this may be a more politically palatable method than reducing tolerance of speeding to 0 km/h. A variation of this scheme is in place in New South Wales, Australia where a discount is provided on the driver licence renewal fee if there were no driving offences in the previous five years, however this only amounts to $83 every five years, which is arguably too low and too infrequent and still relies on current, limited, enforcement.

The finding that the highest risk drivers are also those least likely to change as a consequence of a PAYD scheme is the most important conclusion of this study. It would appear that while impressive reductions in risk are observed in PAYD studies, most of this is due to changes in drivers that could potentially be targeted with less advanced (and lower cost) techniques. That is not to minimise the impact of making drivers aware of their own behaviour and providing some form of financial incentive but a reflection that those drivers with the highest risk driving, and therefore the largest potential benefits, are less likely to change their behaviour. In general, prior to the intervention, study participants could already be divided into two groups, one of which exhibited lower speeding risk scores and was noticeably more engaged in the study. Policy makers would, therefore, be advised to keep in mind the characteristics of the drivers that are likely to be predisposed (to some extent) to change their behaviour following an intervention and should ensure that this is consistent with the intended target of the intervention. This means that for the highest risk drivers it is necessary to impose more stringent penalties for not improving their driving as it appears that awareness and incentives are insufficient to induce change. In effect, avoiding the penalties becomes the motivator to change behaviour rather than the (gain) from the financial incentive.

Future research would benefit from monitoring drivers for a longer phase of time after the removal of the financial intervention, including those drivers that made money in the study to determine if these strategies must be maintained over time or if the improvements are sustained over the long term even after the intervention no longer applies.

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