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Driver feedback during naturalistic driving experiments: A review of types, methods and future challenges

Dimitrios Tselentis[a], George Kostoulas[a], Kleanthis - Nikolaos Kontonasios[a], Petros Fortsakis[a*], George Yannis[b]

[a]OSeven Single Member Private Company, 27B Chaimanta Str., GR-15234, Athens, Greece
[b]National Technical University of Athens, Department of Transportation Planning and Engineering, 5 Heroon Polytechniou str., GR-15773, Athens, Greece

Abstract

Providing targeted feedback to drivers can significantly contribute to the improvement of their driving behaviour and overall safety. However, the effectiveness of the driver feedback provided depends on various parameters. This paper constitutes a systematic effort to review the current state-of-the-art in driver feedback research. The most important parameters that should be taken into consideration when designing such feedback experiments are also reviewed and analysed herein. The focus is on the demographics, the types, the means and the time of feedback of the experiments. Novel ways of providing feedback in a naturalistic experimental setting can be designed based on the review at hand.

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[*] Corresponding author. Tel.: +30-210-684-7777;
E-mail address: pfortsakis@oseven.io

1. Introduction

Road safety is a complicated scientific field of transport research due to the random nature of crash occurrence. Crashes impose serious problems to society in terms of human costs, economic costs, property damage costs and medical costs. According to World Health Organization (WHO, 2018), the total number of road fatalities worldwide continues to climb, reaching a high of 1.35 million in 2016. In the European Union, road crashes were the fifth cause of death in 2016, with roughly six people out of every 100,000 dying on the roads of the European Union due to a road crash. Consequently, understanding the various risk factors that cause road crashes is crucial and has attracted great attention in the literature. Although there has been a very considerable research effort so far, there is still much to be investigated in order to provide insights on the detailed pre-crash conditions and work towards a better proactive safety management in major roads of the transport network. Apart from recording and analyzing driving behaviour, it is equally important to study how feedback on driving characteristics could potentially improve driving behaviour. This paper is a literature review on how user feedback affects driving behaviour in total. This paper is structured based on basic parts of creating an experiment to examine the effects of feedback on driving. Firstly, in Section 2 the demographics of the experiments are described. In Section 3 the experiment types are presented, continuing with a detailed presentation of the types and means the feedback is provided in Section 4. Section 5 analyzes the different approaches that can be followed when providing feedback and finally, this paper conclude to a discussion of the findings.

2. Driver sample demographics

There are various demographics present in driving behaviour experiments. In order to consider user feedback methods and impacts, it is meaningful to initially consider the target group of such information. This is achieved via an examination of past demographic compositions of the various samples of studies published from the relevant literature. For instance, some studies focus on young drivers that may have better response to feedback. Molloy et al. (2018) recruited 100 young drivers (61 male) of ages from 18 to 25 years (Mean M = 21.09, Standard Deviation SD = 2.59), who all held a provisional driver's license (or international equivalent). Participants were University students, recruited through the university intranet website and advertisements and had an average driving experience of 3 years and 2 months (SD = 1.62). Stillwater et al. (2017) used 24 households and 42 individual drivers for a year from a demographically wide range of individuals, from middle to high income, young adult to retired, and single occupant and family households. Brouwer et al. (2015) had 26 professional truck drivers in the experiment, who on average were 50.8 years old (SD = 2.2) and had 28.2 years of driving experience on average (SD = 13.1). Toledo & Shiftan (2016) used an army based sample of 155 vehicles driven by more than 350 drivers for over a year. Most of the drivers (85%) were males, 18–21 years old, mostly during their regular military service - only 30% served in permanent military service. This research was conducted in a military environment, characterized by strict hierarchy and strong discipline.

Mullen et al. (2014) conducted two studies. For the first study, they examined 13 male participants aged 18–24 years and for the second, they examined 28 male participants aged 18-29 years. Horswill et al. (2017) had a sample of 176 drivers with range 17-55 years old. The average age was 23 years (SD 7.03), 59% women and 41% men. The driving experience unaccompanied was 5 years. Another case of studying young drivers is Dijksterhuis et al. (2014). They recruited 60 participants aged 18–25 years old via advertisements; participants had to have held their driver's license for at least one year but no longer than 5 years. An interesting case of recruitment appears in Shimshoni et al. (2015), who used a rolling recruitment procedure. They made phone calls to 6290 drivers immediately after licensure. The candidates that expressed interest in participating were 2380. Of these drivers, 872 candidates completed the web questionnaire. Of the 242 families recruited for the study, 217 were followed up for 6 months. Young participants' age range was 17-22 years (M = 17.5, SD = 0.8). Family participants included 194 fathers (range 33-62 years, M = 50.2, SD = 5.4), and 207 mothers (range 37-59 years, M = 47.6, SD = 4.9). Of the families, in 184 both parents participated, in 10 only the fathers and in 23 only the mothers participated. Among the parents, 53% had academic degrees. Each family received approximately $250 for their participation.

Forty teen-parent pairs participated in the study of Merrikhpour & Donmez (2017). They were recruited via online advertisements, flyers and emails. To be eligible for the experiment, teens (17–19 years) and their parent who was going to participate in the study needed to have at least a Class G2 license (allowing independent driving with restrictions) or equivalent in Ontario, Canada. In a study by Rolim et al. (2014), experiments had 216 bus drivers, while approximately 37% of the drivers belong to the group aged between 36 and 50 years old and are long-term employees of the company. Also, 25% of the drivers belong to the age group greater than 50 years old. In Donmez et al. (2008), 48 individuals between the ages of 18–21, 23 females (M = 20.2, S = 0.73) and 25 males (M = 20.3, SD = 0.89) participated in the study. The participants possessed a valid U.S. driver's license and had at least one year of driving experience. They were native English speakers, they were screened for hearing impairments and colorblindness, and had not driven a driving simulator in the last two years. Participants were compensated 15$ per hour for their participation and had the opportunity to receive up to 10$ extra based on their secondary task performance. The participants of Dogan et al. (2012) were 36 students (11 male, 25 female) from the University of Groningen who held a valid driver license for at least one year (M = 2.5 years; SD = 1.17). The mean age was 21 years (M = 21.22, SD = 1.44); age ranged from 19 years to 24 years. Participants were recruited via the student participant pool of the University of Groningen and received course credit in return for their participation.

Zhao & Wu (2012) studied the behaviour of 30 participants (13 males and 17 females), whose average age was 29.1 years with range 22–44 (SD = 7.9). Participants were screened to ensure that they had good visual acuity and hearing. Additionally, all participants were right-handed, had valid US driver licenses and had driven within the last six months. Farah et al. (2014) recruited 217 families of young drivers aged 17–22 (M = 17.5; SD = 0.8) for one-year period. The analysis of Donmez et al. (2007) consisted of 29 participants: 16 young (M = 19.5; SD = 0.9, 7 male and 9 female) and 13 middle-aged drivers (M = 43.6; SD = 5.5, 7 male and 6 female). All participants possessed a valid U.S. driver's license, had at least one year of driving experience, were native English speakers, and had no driving simulator experience in the last two years. Participants were compensated $15/h for their participation and had the opportunity to receive up to $10 extra based on their secondary task performance. The conducted literature review shows that a large number of participant drivers in driving behaviour experiments is hard to achieve. Most studies in the field have been conducted with less than 100 users. The recruiting methods are usually via local advertisement or approach to highly biased groups like military personnel or drivers with the same profession, or university campuses, while in many cases the participants received compensation.

3. Experiment types

There are two major ways to conduct an experiment, by using (a) real conditions in a naturalistic experiment or (b) a simulation in a more secure contained experiment. Naturally, the type of experiment affects the way drivers are recorded, and feedback is produced and provided to participant drivers.

3.1. Simulated Experiments

Molloy et al. (2018) conducted their research using a simulated environment. The driving simulator was used as a valid and efficient instrument for testing training interventions with young novice drivers. The authors argue that it remains unknown whether the results can be replicated in the operational environment (i.e. on the road). Brouwer et al. (2015) experiment was performed in a truck driving simulator. In Mullen et al. (2015) a driving simulator was used. The authors note that they had an issue with some of the participants that drove above the maximum simulation speed. These participants may have failed to engage more realistically in the driving task due to the low psychological fidelity of the simulator experience. Furthermore, Dijksterhuis et al. (2014), Risto & Martens (2014), Merrikhpour & Donmez (2017), Donmez et al. (2008) and Zhao & Wu (2012) all used driving simulators for the experiments.

3.2. Naturalistic Experiments

Stillwater et al. (2017) conducted naturalistic experiments in California's Yolo, Solano, and Sacramento Counties. Toledo & Shiftan (2016) used naturalistic experiments for 50 weeks and monitored 76,159 driving hours, with an average of 491 hours per vehicle, and 219 hours per driver. Aidman et al (2015) monitored drivers by an infra-red oculography-based Optalert Alertness Monitoring System (OAMS) while they performed their regular driving tasks for a continuous period of 4–8 weeks. Shimshoni et al. (2015) used in-vehicle data recorders that track all trips made by the vehicle and record the following information: (a) trip start and end times, (b) driver identification, and (c) events of excessive maneuvers as defined by patterns of G-forces measured in the vehicle. Dahlinger et al. (2018) and Soriguera & Miralles (2016), both used naturalistic experiments and collected data via smartphone. Rolim et al. (2014) was performed with the collaboration of a Portuguese urban transport operator that had installed devices in buses in Lisbon. In Hutton et al. (2001) participants drove their own car during the experiment. An observer sat in the rear of the vehicle and used time sampling to measure the driver's speeds, following distance and mirror checking. Farah et al. (2014) used In-Vehicle Data Recorders in the participants' cars and Donmez et al. (2007) used in-vehicle information systems in the naturalistic experiments. In Merrikhpour et al. (2014), participant vehicles were equipped with many devices for real trip data collection and driver feedback. Another way for conducting driving behaviour experiments is by using videos. Horswill et al. (2017) used video to test the effect of performance feedback on drivers' hazard perception ability, while Dogan et al. (2012) used video to see the effects of non-evaluative feedback in self-evaluation and performance of the driver.

4. Types and means of providing feedback

Regarding the different types of feedback provided to drivers, the most common feedback categories identified in literature mainly concern overall safety, speed, distraction, drowsiness, headway, fuel economy as well as combinations of the above-mentioned factors such as safety and fuel economy, speed and headways and mirror-checking, headway and speed. Feedback is usually provided through in-vehicle devices (tablet, smartphones etc.), videos, verbally and/or auditorily.

4.1. Overall safety

Regarding overall safety, Dijksterhuis et al. (2015) designed a driving simulator experiment where the sample was divided into 3 groups, the control, the web-feedback and in-car feedback group. Participants were invited to two sessions. In the first session, they were asked to answer some basic demographic questions. Afterwards, they drove three times in the simulator in each session and were told to drive as they would in their own vehicle before each drive. After each drive, participants were presented with a questionnaire and asked to provide driving ratings. In each session, a 10–12 min practice drive without the Pay-As-You-Drive (PAYD) system took place at first and involved the participants driving the test road up until the end of the car following task. During the first session, participants completed a baseline drive before the PAYD drive. During the second session, this order was reversed. A webserver hosted the web-feedback and the website simply displayed the information on their driving behaviour and was not interactive. More specifically, it showed how often the participants had violated the behavioral thresholds and how these violations had reflected their potential reward. The feedback system that was used in the vehicle consisted of a driving user interface (UI) and an end of drive UI, identical to the web feedback information. The in-car driving UI was designed based on an online survey completed by 119 individuals that included several potential UI alternatives. Throughout the experiment, driving UI was constantly updated and provided several types of feedback to drivers, such as the total monetary amount earned, the current speed limit and whether it is exceeded, harsh events i.e. cornering (lateral acceleration in either direction), braking, and acceleration, as well as the threshold value for the penalty on each driving parameter. Apart from that, a warning tone sounded if any of the penalized behaviours took place for more than 6 s, which was repeated every 6 s until the behaviour returned to normal levels.

Shimshoni et al. (2015) randomly allocated the families participated in their experiment to four groups of safety feedback. As for the first group named "no feedback group", neither the parents nor the young driver received any feedback from the In-vehicle data recorder (IVDR) system. Within the second group "individual feedback", the parents and the young driver received feedback from the IVDR system regarding their own driving, but not regarding that of the other family members. The "family feedback" group referred to those families of which the parents and the young driver had access to the IVDR feedback regarding their own driving and the driving of other family members. Finally, regarding the "vigilant care" group, as in the previous group, the parents received a 90-min training session on vigilant care and three to five booster telephone calls, in addition to family feedback. A mixed factorial design with feedback type as a between-subject variable was used by Zhao & Wu (2012) to assess the effect of safety feedback. Participants were equally split into three different groups of (a) no feedback (control group), (b) feedback without driver identity and (c) feedback with driver identity. All participants completed 3 consecutive drives i.e. a drive without receiving any feedback, a drive after one instance of feedback and a drive after a second instance of feedback. Consequently, every drive serves as a within-subject variable. The driving scenario was a 9-mile, two-lane (in each direction) local environment. As part of the driving simulator scenario, there was an intersection with a traffic light at miles 3 and 6. When participants were approaching (200 ft) these 2 intersections, the traffic light turned red for 1 min. The feedback system displayed drivers' performance during the previous section after a participant's vehicle was fully stopped. This way, all three separate drives were segmented, and the three types of driving events were evenly and randomly distributed throughout each drive without any overlap among them. The impacts of real-time feedback on driving safety behaviour using sound signals were assessed by Rolim et al. (2014) considering two monitoring periods. During the first monitoring period (from October 2010 to September 2011) drivers received real-time sound feedback whereas during the second period (from October 2011 to September 2012) drivers did not receive any sound feedback while driving. Data between the two monitoring periods were compared considering the driver and the different buses driven. The main driving indicators analysed were hard stops and starts, extreme accelerations and brakes, time spent idling and excess speed. Results focused on the impact of real-time feedback on driving performance, considering the time spent for each undesirable event.

4.2. Safety and traffic

In order to assess driving safety behaviour feedback impact, Horswill et al. (2017) randomly assigned 176 drivers to four experimental groups which received (a) no feedback, (b) feedback through graph only, (c) feedback through video only and (d) feedback through graph and video. Participants in this study completed two hazard perception tests, one before and one after the experimental interventions, and were also requested to watch a series of video clips on a computer screen. The video clips presented dynamic traffic situations filmed from the perspective of the driver and included potential traffic conflicts. Test instructions directed participants to use the computer mouse and click on road users as soon as they could forecast that the road user would probably be involved in a traffic conflict with the camera car. The time between the first point that the traffic conflict could possibly be predicted and the first time that the participant clicked on the relevant road user was measured. Seventeen video clips were in each test, each one involving a measured traffic conflict. Participants' overall score for each test was obtained by converting their response time to each traffic conflict into a standard score. Consequently, the participant's standard scores for all items in the test were averaged and then the result was converted into an aggregate standard score. Finally, to facilitate interpretation, the participants' aggregate standard score was transformed again into an overall hazard perception response time in seconds. A similar approach was followed by Dogan et al. (2012) who developed a hazard perception test that comprised natural traffic scenes recorded around the city of Groningen, the Netherlands. As for the scoring system, the closer the response of the participant to the starting frame of each hazard situation, the more points were gained. The time frame in which participants responded was also recorded and after the first part of the experiment, participants were provided with feedback in terms of a non-evaluative test scores.

4.3. Speeding

Regarding speed, Molloy et al. (2018) randomly assigned participants to five groups and tested over three different occasions. Speed management behaviour was evaluated using data collected from the driving simulator in low and high-speed zones (40 km/h and 80 km/h) in all three sessions. The five groups into which drivers were divided involved (a) control (no feedback), (b) performance feedback, (c) performance and financial feedback, (d) performance and safety feedback and (e) combined feedback (performance, financial and safety) group. The three sessions occurred (a) immediately after training, (b) one week following training, and (c) six months after training. The two dependent variables selected that characterize speed management behaviour were mean speed (km/h) and percentage of time speeding (%) in the 40 km/h and 80 km/h speed zones. These variables were selected as the most common parameters that characterize speed management behaviour, and were considered complementary to each other. The authors chose mean speed because it summarized the speeding behaviour of the participants and percentage of time speeding because it provides an extreme measure of speeding performance. In Molloy et al. (2018) four out of five experimental groups received post-drive feedback verbally about their speed related performance, after the baseline drive. As mentioned above, the control group received no feedback, whereas the performance feedback group received feedback about their driving performance related to speed during the baseline drive. Feedback included the number of speed limit violation in each speed zone, mean speed exceedances, and maximum speed exceedance in each speed zone. Performance and finance feedback group received feedback about their performance and potential fines/financial infringements that could be received for the speed exceedance during driving. Performance and safety feedback group received feedback about their performance and potential safety outcomes for them and their passengers and combined feedback group received feedback about their performance, financial infringements and safety outcomes.

Participants in Mullen et al. (2015) also received feedback on speed behaviour through a simulated speed feedback device. After they were instructed to drive as they would normally do in a real vehicle, all participants completed the orientation drive. Afterwards, the feedback device and token economy were explained to all participants that belonged to the experimental group. Following this, the participants of both the experimental and control group completed the test drive with and without the intervention, respectively. Drivers in the experimental group earned 1 point for every 15 s that they drove at or below 93.5 km/h. This was used only for the experimental group and consisted of a black rectangle with a green and a red circle or 'light'. The green light was continuously illuminated while drivers travelled at or below 93.5 km/h; the red light illuminated when drivers drove above 93.5 km/h. This allowed drivers to travel up to 3.5 km/h above the speed limit of 90 km/h . This 3.5 km/h window ensured that drivers could maintain the speed limit without receiving negative consequences for minor speed fluctuations.

4.4. Distraction

Regarding distraction, Merrikhpour & Donmez (2017) administered feedback as a between-subjects variable (social norms, post-drive, real-time, and no feedback). Regardless of the feedback type received, each participant completed five experimental drives while performing a secondary task, and therefore driving was a within-subject variable. The first drive did not involve any feedback and was identical across all feedback types, establishing a baseline driving performance under a state of self-paced distraction without feedback. The rest of the drives were differentiated across the feedback conditions. A comparison of their distracted driving behaviour to that of their parent was provided to the teens in the form of social norms feedback consisted of a post-drive report. The parents assigned to this condition were invited to a laboratory to perform the simulator experiment before their teens and completed the five experimental drives while engaging in the secondary task. The teens were invited to the laboratory afterwards and conducted the five experimental drives as well but were also presented with social norms feedback at the end of each of these five experimental drives. Parents were asked not to disclose any information about the experiment to their teenagers, to ensure that the teens were not aware of this deception. Donmez et al. (2007; 2008) investigated the impact of feedback on distraction through a simulator experiment conducted using (a) an eye-tracking device and (b) a 7-inch touch-screen LCD that provides the visual messages for the secondary task as well as feedback to drivers. All participants had to complete one practice drive and four experimental drives. The participants were grouped as follows: (a) no feedback, (b) retrospective feedback and (c) combined concurrent and retrospective feedback. All participants completed four consecutive drives in order to increase the amount of exposure to feedback. Participants completed these drives while performing an in-vehicle secondary task, which was considered to distract participants. The group with retrospective feedback received a trip-report after each drive. If no critical incidents took place during the drive, participants received positive feedback in order to increase driver acceptance of the trip-report. Incidents occurred in 40 of the 68 drives in the retrospective feedback condition and in 38 of the 56 drives in the combined feedback condition in this experiment. In the case of an incident, a timeline showed the incidents (long red bars), appropriate responses to lead vehicle braking (long green bars), and the locations of the distractions to the users.

4.5. Drowsiness

Aidman et al. (2015) monitored the drowsiness of 15 Army Reserve personnel and examined the effect of providing participants with feedback on their drowsiness condition.

A repeated-measures cross-over design was used in this study to test the effect of Orbit Attitude and Maneuvering System (OAMS) feedback on objective drowsiness, subjective sleepiness and self-rated driving performance. Participants drove using Optalert glasses on and data were continuously recorded by an in-vehicle OAMS. Approximately half the time they drove with the OAMS feedback switched on (feedback On condition) and the other half with the feedback switched off (feedback Off condition). A single cross-over point was used in the design to counterbalance the order of these conditions. With the restriction to produce two groups of near equal size, participants were randomly allocated to these conditions. Consequently, eight participants were allocated to the On-first condition (they began their driving with feedback On, and the remaining seven participants started with feedback switched off (Off-first condition). The participants crossed over to the alternative condition at half-time mark of each one's participation.

4.6. Headway

In order to examine headway, Risto & Martens (2014) conducted a study with 2*2*3 repeated measures design support (discrete headway feedback vs. no headway feedback) as a between participant factor and direction of headway adjustment (increase vs. decrease) and speed of the lead vehicle (50 vs. 80 vs. 100 km/h) as within participants factors. In order to prevent the use of distance information from supported trials as an orientation in unsupported trials, feedback support was made a between participants factor. Additionally, to indicate the accuracy of the chosen headway, the absolute headway estimation error, the absolute difference between the instructed headway and the headway chosen by the participant, was operationalized. Desktop speakers, placed on the dashboard, were used to play the pre-recorded headway instruction, as well as the discrete headway feedback. The discrete headway feedback had the form of a tone and indicated the moment at which the current time headway of the participant's vehicle to the lead vehicle matched the instructed time headway. The sound was played only once at the first crossing of the instructed headway and no further tone would be produced at any subsequent crossing in either direction.

4.7. Eco driving and fuel economy

Stillwater et al. (2017) and Stillwater & Kurani (2013) followed a similar approach conducting a driver feedback experiment for eco driving. Households for the feedback experiment were selected from a pool of users who participated in a Plug-In Hybrid Electric Vehicle (PHEV) demonstration that took place. Each vehicle was outfitted with a custom feedback device measuring 7 by 5 inches located over the standard centre console screen. Only the PHEV battery state of charge was shown by the device during the first phase, simulating information that a commercial PHEV might have. The feedback device showed a variety of energy economy, cost, and emissions information in user-selectable panels at the beginning of phase 2, with no eco-driving advice or encouragement given. A driving simulator experiment was performed by Brouwer et al. (2015) to assess the eco-driving performance and the impact of feedback on it. A combination of hardware and software components was used for the visualization. The entire visualization had a range of 180° front view and a 120° back view. Eco-driving feedback was provided using a tablet located at the top of the instrument cluster in the middle of the dashboard. At the beginning of the process, all drivers drove during a short session to get used to the driving simulator, followed by the baseline condition, in which they drove without an ecosystem installed. Afterwards, all participants drove with the basic display and then half of the participants drove with the learning goal orientation display at first, followed by a driving session with the performance goal orientation display, and the rest of the participants vice versa. Dahlinger et al. (2018) implemented a field experiment, by developing and deploying a system that collects driving and location data, provides visual eco-driving feedback via a smartphone app and transmits the data to a backend system. The feedback system consists of (a) an on-board diagnostics (OBD2) device for vehicle driving recording, (b) a smartphone device as the user interface and uploads the data to (c) the backend server, were all data are stored for analysis. Driving data were sent via Bluetooth to a smartphone that provides visual feedback based on several driving data parameters. Two types of feedback served as treatments of driving-feedback unrelated to fuel consumption, which the control group received. The authors were able to remotely control which of the feedback screens was provided to the driver for every system and at any time. The main difference between the two types of eco-driving feedback used is related to the display of fuel consumption (a numeric vs. a symbolic way (abstraction)), where real-time fuel consumption values (no aggregation) were used for numeric feedback and a 3-minute moving average (aggregation) of fuel consumption was used for symbolic feedback.

5. When should feedback be provided?

Most studies conclude that feedback is improving drivers' behaviour, but the question remains: When is the feedback more effective? Dijksterhuis et al. (2015) try to answer that question by experimenting on providing immediate feedback within the vehicle itself and with a delayed web-based interface, which is presented temporally separated from driving. The results indicate clear driving behaviour improvements for both methods as compared to baseline rides and an equally sized control group. They conclude that the initial advantage of the in-car group was reduced substantially. When considered together with usability ratings and driving behaviours in specific situations, these results show a moderate advantage of using immediate in-car feedback. The study also showed that under conditions of feedback certainty, the effectiveness of delayed feedback approaches that of immediate feedback as compared to a naive control group. In Molloy et al. (2018) the participants received verbal feedback after the first baseline drive of the experiment. Stillwater et al. (2017), Brouwer et al. (2015) and Dahlinger et al. (2018), all had an in-vehicle feedback device that was enabled after the baseline phase. In Toledo & Shiftan (2016) research the feedback was provided at 3 stages after a blind stage of 8 days period.

In Mullen et al. (2014), feedback is provided during the driving simulation. The authors mentioned that most drivers are aware of it while speeding and that feedback may be more effective for drivers that are not conscious speeders. Likewise, Risto & Martens (2014) used a discrete feedback during simulations. Zhao & Wu (2012) had real-time feedback during the simulations. The driving feedback in Shimshoni et al. (2015) was conveyed in two ways: by an in-vehicle display (immediate feedback of three lights [green, yellow, red] that would light up during driving) and by a web-based application (cumulative feedback that could be viewed at any time). On the other hand, Soriguera & Miralles (2016) provide feedback after each drive, whereas in the case of Merrikhpour & Donmez (2017), the feedback was provided both during and after the experiments. In Rolim et al. (2014) the drivers received real-time sound feedback while driving the instrumented buses. Donmez et al. (2008) study assessed the effects of retrospective only and combined concurrent and retrospective feedback on driving performance and driver engagement in distracting activities. The results showed that driving performance improved from the first to last drive for all conditions, suggesting a learning effect, which was enhanced by feedback. The feedback in Farah et al. (2014) was given in real time and after each drive. Similarly, the study of Donmez et al. (2007) was designed to test real-time feedback that alerts drivers based on their off-road eye glances. In the case of Merrikhpour et al. (2014), there was an in-vehicle display, namely A LED changed colours based on the real time performance. After the trips the participants received rewards based on their performance. The feedback in the drowsiness experiment in Aidman et al. (2015) was real-time on driver performance and levels of alertness. An immediate feedback was provided by the co-driver in Hutton et al. (2001). In Dogan et al. (2012), feedback was presented after each video clip that informed participants about the score obtained for the particular clip.

6. Discussion

This paper constitutes a systematic effort to gather, group and present the most scientifically strong studies in literature relevant to driver feedback. Information related to the type and time of feedback as well as the means of providing it are collected and presented herein, while the results of this review are summarized in table 1. Findings indicate that the ultimate objective when providing feedback to drivers is to trigger drivers' learning and self-assessment process and enable them to gradually improve their performance and monitor their evolution. This is a very important process since it will have a significant effect on the human factor in driving, which is the main cause of traffic accidents, and will lead to the avoidance of near-accident situations and ultimately, to the reduction of the total number of accidents. These might include the establishment of detailed cause-effect relationships between aggressive driving and the associated risk, which provide valuable information for road safety improvement. This could also be useful for insurance companies, applications for vehicle fleet management, geolocation of dangerous spots in a road network or serve as a tool for objective proving driving behaviour, in order to qualify for premiums in vehicle insurances or for being retrieved the driving license after a revocation. Finally, it was found that there is a wide range of means to provide feedback to drivers based on their behaviour such as in-vehicle devices, monitors, sound alerts, verbally, smartphones and web portals.It is also shown (Dijksterhuis et al., 2015) that the presence of multiple risk-related driving behaviors during driving is substantially reduced by a broad PAYD insurance that is based on these driving behaviors (Tselentis et al., 2017). Therefore, the usage of a behaviour based PAYD system could lead to a further increase of the benefits of a purely mileage-based system. Compared to a control group, the vast majority of the positive effects apply to both the delayed and immediate feedback systems. On the other hand, it is implied that a crucial factor for the effectiveness of a PAYD system is the certainty of viewing feedback and not its immediacy. The authors draw the conclusion that the debate on whether it is preferable to provide real time or web-based feedback should be shifted to how the certainty of feedback, preferably in real world settings could be maximized. It is highlighted (Dijksterhuis et al., 2015) that the next step in investigating the impact of PAYD for both the individual driver and society should be future experimental studies of actual PAYD products. The research of Stillwater et al. (2017) concluded that eco-driving feedback effects vary by cognitive grouping, drive cycle, and baseline performance. In other words, shorter trips, more technically oriented drivers, and low-efficiency drivers demonstrated the greatest reductions in energy consumption between periods that feedback was provided and periods that feedback was not provided. Based on the initial (pre-feedback) responses to a behavioural questionnaire, the two groups of drivers who had distinct energy outcomes were described. Low knowledge of fuel economy, low interest in fast driving, and high technical competency was demonstrated by those drivers that were mostly influenced by feedback.

When separated into these cognitive groups, even though the group did reduce freeway speeds, the Fast & Unsure group did not reduce fuel consumption in the presence of feedback. This group was found to be confused by the feedback received and tried unsuccessfully to reduce fuel consumption. The simultaneous reduction in self-reports of MPG knowledge and confidence indicates that this group may benefit from additional training or education to help achieve the possible reductions.

Table 1. Driver feedback literature summary.

Reference	Sample size	Drivers	Experiment type	Feedback regarding	Feedback through	Time of feedback
Molloy et al., 2018	100 (61 males)	Young	Driving simulator	Speed	Verbally	After the 1st drive
Stillwater et al., 2017	42	All	Naturalistic experiment	Fuel economy	In-vehicle device	At real time
Brouwer et al., 2015	26	Professional truck drivers	Driving simulator	Fuel economy	In-vehicle device (Tablet)	At real time
Toledo & Shiftan, 2016	350+	All	Naturalistic experiment	Safety and fuel economy	Verbally and written report	After the 1st drive
Mullen et al., 2015	15 and 28	Young	Driving simulator	Speed	In-vehicle device	At real time
Dijksterhuis et al., 2015	60	Young	Driving simulator	Safety	In-vehicle device and web	At real time and after the 1st drive
Horswill et al., 2017	175	All	Video	Safety	Video and/or Graph	After the 1st drive
Aidman et al., 2015	15	All	Naturalistic experiment	Drowsiness	Optalert Alertness Monitoring System (OAMS)	At real time
Shimshoni et al., 2015	217	All	Naturalistic experiment	Safety	In-vehicle device and web	At real time and after each drive
Dahlinger et al., 2018	62	All	Naturalistic experiment	Fuel economy	Smartphone	At real time
Soriguera & Miralles, 2016	7	All	Naturalistic experiment	Safety	Smartphone	After each drive
Risto & Martens, 2014	20	All	Driving simulator	Headway	Sound	At real time
Merrikhpour & Donmez, 2017	40	Young	Driving simulator	Distraction	Auditory alert and report	At real time and after each drive
Rolim et al., 2014	216	All	Naturalistic experiment	Safety	Sound	At real time
Donmez et al., 2008	48	Young	Driving simulator	Distraction	In-vehicle device	At real time and after each drive
Hutton et al., 2001	2	All	Naturalistic experiment	Mirror-checking, headway and speed	Verbally	At real time
Dogan et al., 2012	36	Young	Video	Safety	Report	After each drive
Zhao & Wu, 2012	30	All	Driving simulator	Safety	Visual and auditory	At real time
Farah et al., 2014	217	All	Naturalistic experiment	Safety	Verbally	After each drive
Donmez et al., 2007	29	All	Driving simulator	Distraction	In-vehicle device	At real time
Merrikhpour et al., 2014	37	All	Naturalistic experiment	Speed and headways	In-vehicle device	At real time
Stillwater & Kurani, 2013	46	All	Interviews	Fuel economy	-	-

Compared to the baseline period, the group of Techie Trainee group had a statistically significant 5.5% reduction in fuel consumption in the feedback period. This reduction was related to the initial cognitive factors of the group when baseline performance was taken into account. As indicated by the strong influence of baseline performance, high-performing drivers, i.e., drivers already achieving low energy consumption (high fuel economy) in their baseline period were not influenced by the feedback received. It is indicated by this performance ceiling that in order to be more effective for this subgroup and to help engage this group in further energy-saving behaviours, additional forms of feedback that influence non-eco-driving, but energy-relevant, behaviours such as carpooling, mode-shifts, purchases of higher fuel efficiency vehicles, or other behaviours.

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