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ABSTRACT

Introduction: Fatal highway incidents remain the leading type of fatal work-related event, carrying tremendous personal, social, and economic costs. While employers with a fixed worksite can observe and interact directly with workers in an effort to promote safety and reduce risk, employers with workers who operate a motor vehicle as part of their job have fewer options. New technologies such as on-board safety monitoring systems offer the potential to further improve safety. These technologies allow vehicle owners to collect safety-specific information related to a driver’s on-the-road behavior and performance. While many such devices are being developed and implemented in both commercial fleets and private vehicles, the scientific examination of these devices has lagged by comparison. Method: In the current paper, we: (a) describe the general features and functionality of current generations of on-board monitoring devices and how they might impact various driver behaviors; (b) review the current state of scientific knowledge specific to on-board devices; (c) discuss knowledge gaps and potential areas for future research, borrowing from the related domain of computer-based electronic performance monitoring (EPM); and (d) propose a framework that can be used to explore some of the human-system interactions pertaining to monitoring systems. Impact on Industry: Motor vehicle crashes can carry tremendous costs for employers, in terms of injury, disability, and loss of potentially productive work years. New technologies can offer tremendous benefits in terms of promoting safer on-the-road behaviors.

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Efforts to reduce risk and improve workplace and highway safety are as important now as ever before. In the United States in 2009, there were over 5.5 million police-reported crashes, accounting for 30,797 fatalities and over 1.5 million injuries (National Highway Traffic Safety Administration [NHTSA] [NHTSA], 2010). Although the number of highway incidents fell 21% in 2009, the 882 fatal highway incidents remained the leading type of fatal work-related event, accounting for nearly two-fifths of all fatal work injuries (Bureau of Labor Statistics [BLS] [BLS], 2010). The financial impact associated with both fatal and non-fatal work-related highway incidents places a substantial economic burden on employers. According to the 2010 Liberty Mutual Workplace Safety Index, an investigation of the leading causes of serious workplace injuries, the financial impact associated with non-fatal work-related highway incidents cost employers an estimated $2.3 billion in direct costs.

Whereas the employer with a fixed worksite has the opportunity to directly observe workers and interact with them in an effort to reduce risk, the employer with workers who operate a motor vehicle as part of their job has fewer options. Driver safety intervention strategies have typically involved driver screening and selection, driver training, and vehicle maintenance. While these approaches have had some success, new technologies such as on-board safety monitoring systems offer the potential to further improve safety (e.g., Toledo, Muscanat, & Lotan, 2008; Wouters & Bos, 2000). These technologies allow vehicle owners to collect safety-specific information related to a driver’s on-the-road behavior and performance. The devices can be configured to automatically store data surrounding a critical event for later download and subsequent review. In this way, data derived from these devices can be reviewed for safety-critical learning opportunities. Some devices also provide drivers with real-time feedback following a critical event. Knipling (2009) noted several benefits of using such systems in commercial fleet operations: (a) the system can document specific behaviors that might lead to crashes, incidents, or traffic violations and thereby provide an opportunity for proactive corrective feedback; (b) the feedback and related evaluations are objective, timely, and frequent; (c) drivers can receive positive feedback and rewards for good behaviors (these rewards can also be structured to reinforce group or fleet-level achievements); (d) benchmarks for driving behaviors can be set in order to establish carrier or group norms and expectations; (e) these systems may replace time-consuming ride-along observations. It follows that, for commercial drivers, the application of these devices is intended to promote and
encourage safe behaviors. In addition to safety considerations, such devices can be used to improve productivity and efficiency, as well as aid with compliance with regulations and identify situations where liability is a concern. However, application of these devices is not confined to commercial fleets. Developers of these systems are now marketing this technology to parents of teenage drivers as a means of extending parental monitoring into the vehicle (e.g., Farmer, Kirley, & McCartt, 2010; McGehee, Raby, Carney, Lee, & Reyes, 2007).

As is the case for most technologies, the development and realization of new devices and systems has greatly outpaced the rate of rigorous scientific exploration of the implications, benefits, and costs of the systems. In the current paper, we aim to:

- Describe the general features and functionality of current generations of on-board monitoring devices and how they might impact various driver behaviors.
- Review the current state of scientific knowledge specific to safety monitoring systems.
- Discuss knowledge gaps and potential areas for future research, borrowing (in some cases) from the related domain of computer-based electronic performance monitoring (EPM).
- Propose a framework (based on Brunswik’s lens model) that can be used to explore some of the human-system interactions pertaining to on-board monitoring devices.

On-Board Safety Monitoring Systems

On-board safety monitoring systems have become increasingly sophisticated in recent years, concomitant with the growth and development of wireless and other telecommunication technologies. As a result, they are becoming increasingly prevalent in commercial and private motorist applications. Many such devices are essentially “black boxes” that passively gather data from a variety of sources. Some of these tap directly into the vehicle on-board diagnostics (OBD II), while others might have embedded GPS functionality, built-in accelerometers, or other features. Naturally, devices vary considerably in terms of sophistication and the number of features and the data that can be extracted. For example, there are numerous vehicle or driver parameters that might be monitored via these systems. Performance data that can be extracted include vehicle speed and location, acceleration and braking patterns, and fuel consumption. Some systems also provide video of the traffic environment as well as inside the vehicle, offering contextual details surrounding critical triggering events as well as an indication of what drivers are doing, including instances of seatbelt non-compliance, inattention and distraction, fatigue or other behaviors or driver states (e.g., Misener et al., 2007). Many devices utilize custom algorithms, based on monitored inputs, to determine whether or not noteworthy events have occurred. These algorithms, often proprietary though sometimes user-modifiable, are likely as varied as the devices themselves.

Depending on the system, monitoring devices log data continuously or store only those data surrounding events where some predefined threshold is exceeded. (e.g., G-force threshold). Data download might be performed manually or automatically (wirelessly). In some cases, vendors of this technology provide data management services in which events and driver behaviors are logged, reviewed, and summarized. Systems also vary in terms of their conspicuity. Some systems (e.g., those that are connected to the vehicle OBD II) might be completely hidden from view and perhaps outside a driver’s awareness. Other systems are more salient, such as those that are positioned within the field of view of the driver (e.g., those with video output), or those that provide drivers with performance feedback while on the road.

The present review is limited to those systems that provide some form of feedback, whether immediate or delayed, with the goal of elicit changes in subsequent driver behavior and safety. As such, scientific efforts such as naturalistic driving studies, which gather similar data for the purposes of understanding causal factors in crashes and near misses, are beyond the scope of this review. We further distinguish feedback and data logging systems from variations of collision warning systems, which provide drivers with real-time information in the form of alerts or warnings of a collision, lane departure, or similar outcome that will occur unless some corrective action is taken. These systems, though useful in their own right, have a fundamentally different role in driver safety. While some on-board devices do provide drivers with in-vehicle feedback (e.g., an LED indicator that the device has been triggered and the data logged), this information does not occur in advance of a collision or near miss, but instead follows it.

As discussed elsewhere (e.g., Misener et al., 2007; Sherry, 2001), research and development of on-board monitoring devices should ideally: (a) identify and validate behaviors that may be precursors to crashes or injuries; (b) be based on cost-effective ways to monitor behavior; (c) identify the most effective ways to provide feedback that encourages safe behavior and discourages unsafe behavior; and (d) establish management and driver acceptance of the program. The last step involves a consideration of logistical, legal, and privacy issues concerning the data obtained from the on-board devices.

On-Board Safety Monitoring Systems and the Task of Driving

The driving task is commonly characterized as a function of three levels of control: strategic, tactical, and operational (Michon, 1985). Strategic control operates over a longer time frame (minutes to hours or longer) and includes activities such as trip or route planning. Tactical control, in the seconds to minutes time frame, encompasses a variety of maneuvers according to dynamic traffic conditions. These might include car following, lane changes, or passing behaviors. Finally, operational control refers to the low level activities that occur, second to second, in support of vehicle control, such as pedal or steering inputs. As illustrated in Fig. 1, environmental or situational factors, including road, weather and traffic conditions or configurations can influence each level of the driving task. For example, following distance might vary as a function of road type (urban, low speed vs. rural, high speed) or weather conditions (wet vs. dry surface conditions).

![Fig. 1. Conceptual framework for discussion of on-board safety monitoring systems in the driving context. Factors related to the Organization and Driver are illustrative and should not be considered exhaustive. For private motorists, the Organization framework can be substituted with a familial context, including factors related to parenting style, vehicle availability, etc.](Image)
Studies of On-Board Driver Monitoring Devices

Several studies have examined the impact of a variety of safety monitoring systems on driver performance and behavior. The prototypical study of this genre involves the installation and implementation of a single (or a few) system(s) in a fleet or a group of drivers, followed by an assessment of subsequent safety behaviors (e.g., crash involvement, frequency of safety critical events). The studies are summarized in Table 1 and capture both commercial drivers and private motorists, specifically, teenage drivers. The devices employed in these studies varied by type, timing, and extent of feedback provided to the drivers.

Based on the studies described in Table 1, we note generally favorable shifts along the variables of interest, following implementation of the device. These variables include incidence of collisions or costs savings for the organization (where relevant), reduction in trigger events thought to relate to safety and productivity, or reductions in derived measures of risk such as those described above. For example, Hickman and Hanowski (2001) reported 37% and 52% reductions in safety-related events per 10,000 miles in two commercial carriers following implementation. Similarly, Lehmann and Cheale (1998) found crash reductions of up to 30% for fleet drivers after the implementation of monitoring systems. However, a few studies offer evidence that the effects of the intervention are not sustained indefinitely—the rates return to pre-treatment levels after a period of time, which varies across study (ranging from 4 to 10 months in the reported studies; e.g., Toledo & Lotan, 2006; Musicant, Lotan, & Toledo, 2007). Therefore, it has been suggested that strategies to promote continued engagement in the process should be part of any such implementation. As an example, McCart et al. (2010) found that parents (of teenage drivers) who declined participation in a study of such devices usually did so because of concern over privacy issues or fear of jeopardizing trust with their teenager. Additionally, although the parents found the online reporting system useful, they indicated a preference for receiving a non-web based report—a fact that might have contributed to declines in web site visits over time. It follows that initial buy-in for the implementation of these systems, as well as the nature of the feedback, would be equally important in commercial settings. Finally, at least one study suggests that subgroups of drivers might account for the majority of triggering events and that these subgroups would stand to achieve the greatest safety gains arising from the system (see also Knipling, 2004).

Although the cumulative outcomes of these research studies are suggestive, it is important to remark on the inherent challenges associated with this type of research. Although many studies employ an acceptable sample size, the outcome measures are often relatively infrequent such that a small change in frequency from one measurement period to another could constitute a large proportional change. Another challenge is in the selection and application of the appropriate baseline condition for comparative purposes. These studies typically employ a case-crossover design, wherein data are amassed for a period of time before the feedback or system is implemented. While this affords control of within-driver variability, it may not allow for a counterbalanced design. To help offset this problem, some studies employ a post-treatment baseline condition. Other approaches have tried to match groups, but therein lie other challenges associated with the control of a multitude of extraneous factors that can influence the results. As noted earlier, sometimes the mere presence of the device can impact behavior—even in the absence of any type of feedback (i.e., a Hawthorne effect). While any resulting shifts toward safer behaviors should be seen as favorable, this potential makes it difficult to pinpoint causal factors. The deployment of additional control conditions would help overcome this challenge, though these studies tend to be expensive and labor-intensive. Finally, we note that there is a bias toward publishing significant results in the scientific literature. This so called “file drawer problem” (i.e., studies of null effects reside in filing cabinets, unpublished) can mask the true magnitude of the effect size.

Knowledge Gaps and Future Research Needs

Even a cursory inspection of the above-referenced literature would suggest that there are many research questions that have yet to be addressed. Many investigations have been limited to examining the impact of a given system on the aspects of behavior or safety
<table>
<thead>
<tr>
<th>Driver Type</th>
<th>Study Design</th>
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<th>Feedback Type</th>
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<tr>
<td>Toledo and Lotan (2006)</td>
<td>Drivers of company cars; N = 33</td>
<td>Blind-profiling stage (1-2 mos) followed by Feedback stage</td>
<td>Risk Index based on driver and trip-level classifications&lt;sup&gt;3&lt;/sup&gt;</td>
<td>Delivered via website; own performance, company performance (for comparative purposes)</td>
</tr>
<tr>
<td>Toledo et al. (2008)</td>
<td>Company drivers; N = 191</td>
<td>Blind-profiling stage followed by Feedback stage</td>
<td>Risk Index based on driver and trip-level classifications&lt;sup&gt;3&lt;/sup&gt;</td>
<td>Delivered via website; own performance, company performance</td>
</tr>
<tr>
<td>Musicant et al. (2007)</td>
<td>6 organizations; N = 103</td>
<td>Blind-profiling stage followed by Feedback stage</td>
<td>Risk Index based on driver and trip-level classifications&lt;sup&gt;3&lt;/sup&gt;</td>
<td>Delivered via website; own performance, company performance</td>
</tr>
<tr>
<td>Wouters and Bos (2000)</td>
<td>11 vehicle fleets: medium &amp; heavy trucks, coaches, taxis, vans, company cars (840 vehicles total, 270 equipped with data recorder)</td>
<td>Matched control design – separate control and treatment groups</td>
<td>Accident data recorder (data just before and right after a crash); Journey data recorder (time schedules, mean speed, rapid accelerations and decelerations, fuel consumption)</td>
<td>Protocol for feedback not specified</td>
</tr>
<tr>
<td>Levick and Swanson (2005)</td>
<td>Ambulance drivers (&gt; 250 drivers)</td>
<td>Baseline stage (3 mos) followed by Feedback stage (15 mos)</td>
<td>Vehicle speed, hard acceleration and braking, cornering velocity, g-forces, signal use, seat belt use, parking brake, rear-facing sensors</td>
<td>Real-time auditory feedback whenever preset tolerances were exceeded for any given parameter; Penalty counts tracked over time, but not clear whether delivered as feedback</td>
</tr>
<tr>
<td>Lehmann and Cheale (1998)</td>
<td>Variety of vehicle fleets</td>
<td>Fleet management variables; lateral &amp; longitudinal acceleration, speed, indicators, signals, ignition, brake activation, Variables recorded 30 sec before and 15 sec after a collision.</td>
<td>Details regarding feedback not provided</td>
<td>• Reduced crash involvement (up to 30% reduction)</td>
</tr>
<tr>
<td>McGehee et al. (2007)</td>
<td>Rural teenage drivers; N = 26</td>
<td>3 Phases: Baseline, Intervention, 2nd Baseline</td>
<td>Event-driven video-monitoring system monitored acceleration (G-forces) and captured video and audio for 10 sec before/after triggering event.</td>
<td>LED on device indicated device triggered; Parental feedback with weekly video review and graphical report card (along with comparison to peers)</td>
</tr>
<tr>
<td>Lotan and Toledo (2005), Lotan et al. (2009)</td>
<td>Younger drivers and parents</td>
<td>Baseline stage followed by Feedback stage</td>
<td>In-vehicle data recorders</td>
<td>Personal data delivered via website</td>
</tr>
<tr>
<td>Farmer et al. (2010)</td>
<td>Young novice drivers; N = 85</td>
<td>3 Phases: Baseline (2 wks), Treatment (20 wks), Post-treatment (2 wks); Control group with no alerts and no online feedback</td>
<td>Sudden acceleration or braking, speeding, seatbelt use</td>
<td>Immediate in-vehicle feedback (with notification via website or with 20-second grace interval in which behavior could be corrected without notification); Parental access to performance data on web</td>
</tr>
<tr>
<td>Hickman and Hanowski (2011)</td>
<td>Commercial truck drivers in 2 carrier fleets</td>
<td>Baseline stage (4 wks) followed by Feedback stage (13 wks)</td>
<td>Event-driven video-monitoring system monitored acceleration (G-forces) and captured video and audio for 10 sec before/after triggering event.</td>
<td>LED on device indicated device triggered; managers could access recorded safety events and follow a coaching protocol.</td>
</tr>
</tbody>
</table>

Note: 1 Risk Index takes into account the types, numbers and severity of ‘tagged’ maneuvers (e.g., e.g., hard braking, excessive speeds, sudden braking, etc.) as well as other indices such as trip-level risk index, speed index, driving patterns, and fuel consumption index.
purportedly measured by said system. Moreover, these investigations often lack a strong theoretical framework. This should not be con-
strued as directed criticism of this body of work. Indeed, these studies represent the critical first steps in our understanding of the role and
influence of on-board driver monitoring systems. Future work should complement and build on this earlier work.

Below, we list several pertinent areas or questions that merit fu-
ture investigation. While this list is by no means exhaustive, we
hope that it offers fair coverage of this important domain.

• Many of the studies of safety monitoring systems employ very
course measures of safety and performance such as collision in-
volvelement or the frequency of trigger events, the latter of which
may or may not be valid proxy measures of safety. Moreover, it is
not clear that resulting behavioral responses have safety benefits.
For example, the installation of a device that logs G-force triggered
events might lead to a reduction in these events; however, this does
not offer insight into other aspects of performance and behavior.
Consider the case where, over time, drivers learn the thresholds at
which the system is triggered and adjust their driving to push, but
not exceed the limits (sometimes referred to as “red-lining” in the
aviation domain—an unintended effect arising from the implemen-
tation of advanced ground proximity warning systems and the like).
Further research should be carried out to establish the validity of
such proxy measures as they relate to safety.

• In general, there has been no extensive examination of an array of
systems, including those that offer ranging functionality, from
completely inconspicuous systems tapped into the OBD II to more
visible video capture systems. Many of the currently available stud-
ies instead examine a single or small set of devices. While this ap-
proach provides a valuable assessment of a particular device, it
constrains our understanding of which underlying inputs, mea-
sures, and events are most directly relevant to driver behavior and
safety—particularly those that stand to elicit effective and meaning-
ful behavioral shifts. Ideally, future work should include the system-
atic investigation of not only a range of devices, but of the
underlying features and data. Such an investigation would also
offer insight into the manner in which on-board systems interact
with the different levels of driving control, depicted in Fig. 1.

• There is generally little detail regarding the manner in which feed-
back is provided to drivers. Moreover, while it is generally acknowl-
edged that feedback is a critical component in monitoring systems,
there have been few (or no) systematic efforts to explore what type
of feedback is most effective in eliciting desirable behavioral changes.
For example, for systems that provide both immediate and offline feedback (via web browser or manager/parental inter-
vention), it is not clear whether one type of feedback is better or
sufficient or whether redundancy and reinforcement is necessary.
While some studies have attempted to disentangle the effects of im-
mediate from delayed feedback (e.g., Farmer et al., 2010), it seems
clear that delayed feedback (whether provided by parents or man-
gers of employees) as an uncontrolled, emergent aspect of these
research efforts is highly variable (and, in some cases, non-
existent). For those systems that also offer feedback to the drivers
in situ, there are many other questions regarding how the informa-
tion should be conveyed to the driver. Feedback can be delivered
through multiple modalities (e.g., auditory, visual, tactile, or some
combination) and should consider the implications for driver work-
load and distraction. Ideally, the intrusiveness of feedback should be
commensurate with the urgency of the information to be conveyed.
Future research must involve stronger control or elaboration of the
nature of feedback, such that we can better differentiate between
effective and ineffective forms of feedback. While there are a few
long term examinations of safety and performance implications of
on-board devices, the mixed results concerning sustainability of be-
behavioral changes and safety benefits suggest that more work is
required. Furthermore, it would be beneficial to garner an under-
standing of what organizational factors and related policies will
generate the greatest motivation and accountability to ensure sus-
tained safety benefits. Such work should also be coupled with a
comprehensive examination of feedback mechanisms and their
impact on sustainability.

• Another issue that has not been explored or elucidated in the re-
search specific to on-board safety monitoring systems is the influ-
ence and importance of various organizational factors in the
implementation and ultimate success of commercial applications
of these systems. Some preliminary work has gauged drivers’ initial
impressions of onboard devices (e.g., Huang, Roetting, McDevitt,
Melton, & Smith, 2005; Roetting, Huang, McDevitt, & Melton,
2003); however, more work needs to be done, particularly in the
context of studies where drivers are actually exposed to the systems
(see also discussion by Misener et al., 2007). Of course, this work
would need to be tempered by actual performance results, as
there might be gaps between drivers’ preferences and the system
that affords the best possible safety outcomes.

• In the literature on electronic performance monitoring (EPM) of
office workers, one common outcome is an increase in the level of
stress experienced by the worker under supervision (e.g., Amick &
Smith, 1992; Schleifer, 1992; Smith & Carayon, 1995). It follows
that stress might be an important consideration in the use of perfor-
mance monitoring systems. The impact of arousal and stress on per-
formance follows an inverted-U function, where increases in stress
and arousal will benefit performance up to a certain point. Beyond
that point, however, additional stress and arousal will lead to per-
formance hindrances due to vulnerability to overload of attentional
resources (e.g., Hockey, 1997; Kahneman, 1973). Stress and associ-
ated thoughts (e.g., worry, self-evaluative cognition, negative self-
appraisal, emotion-focused coping) can divert attention away from
task-relevant activities resulting in performance loss and in-
creased crash involvement (McMurray, 1970; Selzer & Vinokur,
1975). Future work in the driving domain should assess the short
and long-term effects of these systems on driver stress and the im-
plications for safety and performance.

• Finally, there has been little work to uncover the social and psycho-
logical mechanisms that account for the observed changes in be-
havior following the implementation of these devices. For example,
in Farmer et al. (2010), it is not clear whether the imple-
mentation of the alerts for seatbelt use and speeding were treated
as reminders for certain desired behaviors or seen as aversive stimuli
that the driver would be motivated to remove through compliance
(i.e., the sounds only stop when the behavior, for example seatbelt
use, is performed). More theoretically motivated work is merited,
the outcomes of which will help inform related-research on effec-
tive feedback and sustainability.

While relatively neglected in on-board monitoring research, feed-
back processes have received much attention in other domains,
such as office and computer work. We supplement the discussion of feed-
back with a brief review of the relevant research from this related
domain and, where possible, provide design recommendations for
feedback for on-board monitoring systems.

Electro nic Performance Monitoring

 Electronic monitoring of workers or operators in situ is not a novel
concept and has been widely examined in computer-based workplace
settings (e.g., Lund, 1992; Schleifer, 1992; Smith & Carayon, 1995;
Smith, Carayon, & Miezio, 1986; Wells, Moorman, & Werner, 2007).
Electronic performance monitoring (EPM) comprises a variety of ap-
proaches to gauge operator performance, productivity, and, in some
cases, safety. While the primary purpose of on-board monitoring sys-
tems is protection of the operator, the primary purpose of EPM is
usually improvement of productivity, as associated with establish-
ment of work standards, error reduction, and, in some cases, task sim-
plication (Schleifer, 1992). However, while we have chosen to focus on 
the safety function of on-board monitoring systems, users of these 
systems may, nonetheless, be sensitive to non-safety-related motiva-
tions for monitoring as well. And this may be the case whether or not 
feedback is provided.

Alder and Ambrose (2005) propose that interpersonal and proce-
dural fairness are key predictors of employee attitudes and performance 
response to EPM. Furthermore, the source of feedback (i.e., face to face 
via supervisor or through a computer), the constructiveness of feed-
back, and the control over feedback are key determinants of perceived 
fairness of EPM and, by extension, on-board monitoring devices. Feed-
back is considered constructive if it is specific, considerate in its tone, 
devoid of threats, and devoid of any internal attributions for poor per-
formance. For on-board devices, these characteristics are more relevant 
for feedback delivered by a third party (e.g., manager or parent) than by 
the system itself (e.g., real-time feedback). Control of feedback includes, 
but is not restricted to, the frequency of feedback delivery or access— 
feedback is perceived as more fair when employees have control over 
the timing and frequency of the feedback. Perceptions of fairness are 
also higher when employees have the ability to provide input into the 
design or implementation of the EPM system, or the extent to which 
EPM-based evaluations can be appealed. The EPM literature suggests 
that the developmental aspects of on-board monitoring should be em-
phasized over punitive aspects. For truck drivers, it is possible that the 
ostensible goals of on-board monitoring actually conflict with other 
management pressures to decrease delivery times.

London and Smither (2002) conceptualized work-related perfor-
ance feedback as part of a longitudinal process influenced by the 
feedback orientation (i.e., individual's overall receptiveness to feed-
back, tendency to seek it out, and likelihood of acting on the feedback 
to guide changes in performance and behavior) and the organization's 
feedback culture (i.e., support for feedback, including the tone of feed-
back, coaching in the interpretation and use of feedback, and a link be-
tween performance improvements and valued outcomes). They also 
discuss the importance of coaching, which can focus on improving 
skills and performance, development opportunities, as well as prob-
lem solving or resolution. Coaching goes beyond simply providing 
feedback; it provides encouragement, conveys expectations, and dem-
onstrates proper, safe or desired behaviors in a non-threatening con-
text. Additionally, critical events (akin to the safety critical events 
gathered by on-board systems) afford the opportunity for valuable 
coaching episodes or learning. These events can lead the individual 
to recognize or seek feedback and to better judge their own capabili-
ties and performance.

Recommendations – Feedback

Although the implementation of on-board monitoring systems in 
a feedback and training setting does not completely overlap with 
insight-based training (described earlier), some of the outcomes of, 
and philosophies adopted by, these approaches should be considered 
by researchers and practitioners of in-vehicle systems. First, insight 
into one’s performance can be an effective means of calibrating 
one’s confidence level to actual risk (i.e., reducing overconfidence).
Second, insight training can lead to more effective outcomes than 
simply knowledge of one’s own errors. This emphasizes the impor-
tant involvement of managers or parents in the feedback cycle. Finally 
(and not unrelated to the second point), the use of actual errors en-
countered in situ can lend itself to more deliberate processing of the 
associated behaviors and consequences and can yield better out-
comes, as a result. However, care must be taken in ensuring that 
learners experience their own errors in a safe, non-threatening 
environment. Otherwise, a focus on errors may draw the learner’s at-
tention to the performance appraisal aspect of monitoring systems,
which, as seen in the research on electronic performance monitoring 
(EPM), can have negative implications for performance.

Based on studies of driver training and electronic performance 
monitoring of workers, we outline a few recommendations related to 
feedback:

• Provide immediate feedback when the unsafe behavior is persistent 
and correctable (e.g., seatbelt usage, following distance)
• The intrusiveness of feedback should be commensurate with the 
urgency of the information to be conveyed
• Feedback should be positive (if possible) and constructive
• Training and development should be emphasized over punishment
• Drivers should experience their errors and not just be told about 
possible errors and their solutions
• Drivers should have a role in the feedback – in the control over the 
timing and frequency or in providing input into the design or 
implementation

System Implementation in the Organizational Context

When it comes to actually implementing a program that includes 
on-board monitoring, there are two broad potential target audiences; 
individual drivers (and their families), and organizations subsuming 
groups of drivers (e.g., commercial trucking companies). In both 
cases, the overall goal is to generate a programmatic structure that 
promotes safer driving behavior. For the individual drivers/families, 
there would likely be a marketing program to motivate individual ini-
tial buy-in along with a support structure that enables and sustains 
continuous participation in the program. For commercial organiza-
tions, once the decision to participate is made by higher management, 
existing safety program structures can be utilized, and individual 
driver participation will likely be part of their assigned duties.

Changing driver behavior can be considered a special case of the 
more general approach to behavior change found within the safety 
management literature. DeJoy (2005) discussed the apparent conflict 
between behavior-based safety and safety culture approaches. Behav-
ior based safety programs, which are generally "bottom-up" in nature, 
have had some history of success. However, the complementary ques-
tion might be: can changing safety culture produce behavioral change 
without the formal programmatic behavior-based structure? DeJoy 
reviews the strengths and weaknesses of both intervention ap-
proaches. Behavior-based programs have specific procedures and 
technologies based on classical psychological principles of behavior 
modification, and well-defined measurable outputs. However, they 
also tend to be "victim blaming," minimize environmental factors, 
and focus only on immediate causes. Safety culture programs empha-
size broad organizational change and focus on basic causes. However, 
the underlying conceptual framework tends to be diffuse and vague, 
and assessment methods are indirect.

DeJoy (2005) argues that a synthesis of both approaches is required. 
Fundamentally, a supportive organizational safety culture is necessary 
in order for a behavior change program to be effective. He presents an 
integrated framework embodying both behavioral and cultural compo-
nents in which the combined strengths can overcome their individual 
weaknesses. While this integrated framework is meant to apply to gen-
eral safety management, there are particular elements that could be 
useful in implementation of safety monitoring systems. This includes 
an organizational problem solving process that attempts to integrate 
cultural contexts, motivational (reward/punishment) factors, and the 
specific behavioral contexts within which driving may be associated 
(e.g., commercial drivers with schedules to meet.)

Framework: Safety Judgments and Lens Modeling

In examining critical incidents in road traffic safety, it is helpful to 
discuss safety-relevant events in the context of human judgment and
decision making. That is, drivers make judgments as to whether their behavior and current outcomes constitute safe driving. Unfortunately, in many situations drivers do not receive feedback regarding their driving performance and simply avoiding a crash does not necessarily constitute a “safe” journey. That said, in the absence of a (very salient) crash, drivers use different bits of information (or cues) to determine whether they have exceeded some safety threshold. For example, they might judge themselves as having acted in an unsafe manner if they were forced to slam on their brakes to avoid hitting a lead vehicle (e.g., a strong vestibular response to the rapid deceleration, screeching tires, or the like). Here the driver might conclude that they were following too closely. Conversely, a much lighter braking incident would not be accompanied by a signification a vestibular response (among other indicators) and thus the behavior might be construed as safe (“I was following at an appropriate distance”). It is important to note that drivers vary considerably in their safety thresholds. As such, safety and perception of safety is subject to considerable variability arising from individual differences, such as in propensity for sensation seeking or differences in risk perception.

In a similar manner, on-board monitoring devices apply algorithms to determine whether a safety-critical event has occurred. Some of the information used by these algorithms is consistent with what the driver herself uses in her safety judgments (e.g., speed and acceleration), while other information may be more subtle or even outside the driver’s awareness. Regardless of who renders the judgment, whether the driver, the monitoring system, or both, models of judgment and decision-making can be useful tools in examining the quality of consistency and correspondence between safety judgments. The lens model, in particular, is well-suited to the examination of judgments that rely on the integration of different bits of information, or cues. The lens model has been widely applied in aviation (e.g., Bisantz & Pritchett, 2003), medical judgments (e.g., Wigton, 2008), weather forecasting (e.g., Stewart, Heideman, Moniger, & Reagan-Cirincione, 1992), and military threat assessment (e.g., Horrey, Wickens, Strauss, Kirlik, & Stewart, 2006), among many other applications.

Lens Modeling

Lens modeling is a technique for exploring the nature and the quality of an observer’s assessment of the state of the world compared to the actual state of the world (Brunswik, 1956; Hammond, 1955). Here, a to-be-judged (environmental criterion) variable and an observer’s judgment of this variable are informed by different information cues (see Fig. 2). These cues will be associated with the to-be-judged criterion to varying degrees, and the observers will weigh these cues differentially in order to render a judgment. The degree to which the judgment reflects the environmental criterion reflects the degree of achievement (i.e., accuracy) for that observer. The lens model can also be used to fit subjective judgments and environmental criterion to linear models and these, in turn, can be used to assess an observer’s consistency in judgment and the environmental predictability for a given pattern of information. The lens model approach can be further elaborated to calculate skill scores as well as indices of regression bias and base rate bias (Murphy, 1988; Stewart, 1990). Full details regarding the computational components of the lens model are beyond the scope of this review; further details can be found in Cooksey (1996) and Kirlik (2006).

In the context of traffic safety, what constitutes the environmental (to-be-judged) criterion? Obviously, this is not straightforward and merits careful consideration, given that there is no universally-agreed upon metric to gauge driver safety. It is more plausible to tailor the lens model to the needs and circumstances of a particular organization. For example, an organization might wish to monitor certain information within their fleet in order to affect positive changes for safety and maintenance costs. Each dimension thus has some bearing on the criterion variable, which can be expressed along a continuum or as a binary event. For example, an organization might wish to establish red flags for certain types of following behaviors, braking profiles, speed, seat belt use, etc. Thresholds or tolerances for each dimension can be guided by subject matter experts, values, and data derived from the scientific literature as well as international standards and guidelines, or can be informed by a given company’s corporate policies. In the context of safety monitoring systems, for a particular organization or application, it could be that the dimensions or thresholds are heavily influenced by the algorithms of the devices themselves, such that there could be a very close correspondence between the system output (i.e., judgment) and the environmental criterion. Even so, the correspondence would not be perfect as there will still be a margin of error, such as the case when the system issues false positives or fails to detect a threshold. This is discussed further below, in the context of n-systems lens models.

N-systems Lens Model

Importantly for monitoring systems, the lens model can be expanded to consider situations where multiple observers or judges are assessing the same environmental criterion. This is referred to as an n-systems lens model and is illustrated in Fig. 3 (Bisantz & Pritchett, 2003; Pritchett & Bisantz, 2006). An n-systems lens model allows for comparison of the judges’ correspondence as well as of their respective models (policy similarity). In practice, judges in the lens model need not be human observers. Automated agents can also be considered in such modeling exercises, such as the case of on-board devices. In these situations, the system and the human will independently use the various cues to determine whether there has been a breach of safety. That is, the driver continues to make judgments regarding safety (Y1, as in the single judge model discussed previously). At the same time, the on-board device renders its own judgment regarding safety (Y2), based on its underlying algorithms. Following from the braking example, the system algorithm might utilize vehicle speed, forward looking radar (to gauge headway distance), and brake pressure sensors or accelerometers to gauge braking and potential impact forces in rendering safety judgments. (Note that these are similar to those cues used by the driver albeit input or processed in different ways—e.g., tri-axial accelerometer versus human vestibular system). Here, the correspondence between the system and driver achievement (Y1,Y2) or, more importantly, disparities between the two can offer insight into fundamental issues of trust and acceptance (e.g., Seong, Bisantz, & Gattie, 2006). As noted above, even if the environmental criterion has been largely aligned with the underlying algorithm of the on-board device, there will remain discrepancies due to signal noise and system intolerances.

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**Fig. 2.** Schematic representation of the lens model. Shown are various information cues (Xn), the weighting of these cues (w), and the judge’s achievement (ra).
It is important to note that the lens model, as depicted here, is more representative of a local system involving the driver and the device. Of course, the underlying computational components can constitute the basis of an examination of broader factors related to monitoring systems, including those outlined in Fig. 1. In particular, achievement or skill scores can be measured and compared in different organizational contexts or situations. For example, one might evaluate achievement in drivers working for organizations with strong safety climates versus ones with poor safety climates. Similar evaluations can be made across different groups of drivers as well, according to some demographic variable or personality trait. It is also possible to expand the n-systems lens model to include other agents as judges (e.g., supervisors), provided they have access to the same information cues as the driver and system. Finally, it should be noted that this framework allows for an investigation into the safety perceptions of drivers as a function of the safety monitoring system and other factors. Accurate perceptions and judgments regarding the state of the world are an important determinant for subsequent behavior. As such, a thorough evaluation of the efficacy and importance of a particular system on bottom line safety and cost savings would need to be complemented by other outcome measures.

Some systems provide drivers with immediate feedback that they have registered and logged a critical event (e.g., an LED indicator on a visible unit might flash to indicate that data are being stored). In such situations, the device itself becomes an additional cue that drivers might use in their own safety judgment. This can be modeled according to a hybrid n-system or hierarchical lens model (Seong et al., 2006), shown in Fig. 4.

In summary, in the context of on-board monitoring devices and driving, the lens model approach allows one to evaluate quantitatively: (a) the achievement of the device in its assessment of safety-critical events; (b) the achievement of the driver in their safety-related judgments (independent of the device); (c) similarities or disparities between the device’s and drivers’ judgments as well as consistency in judgment; (d) the extent to which the device (as a cue itself) influences drivers’ judgments regarding safety; as well as other facets of judgment and decision making. We suggest that this technique and the associated measures will be practical and informative in the examination and evaluation of on-board performance monitoring systems.

**Conclusion**

New on-board safety monitoring systems have the potential to improve driver safety and reduce crash involvement and related costs, by helping address potentially detrimental driving behaviors before they manifest themselves in a crash. These technologies can gather safety-specific information related to a driver’s on-the-road behavior and performance, which can subsequently be used in training or coaching situations. Alternatively, the systems may provide immediate feedback to drivers such that they can correct a negative behavior “on-line”. These devices have typically targeted commercial...
fleets and teenage drivers. Safety notwithstanding, these devices can also help improve fleet operations with respect to efficiency and productivity, thus lowering operating costs.

In the current paper, we review the existing literatures from two related domains: first, we reviewed the existing scientific literature specific to on-board devices in the driving domain. While many studies have demonstrated some safety and behavioral benefits in the use of these systems (whether for employees or teenagers), there are many questions that remain. Thus, we highlight several such knowledge gaps in the hopes that future research efforts can help fill them and thereby enhance our understanding of the implications, both positive and negative, in the implementation of on-board safety monitoring systems in commercial and non-commercial applications. Secondly, many studies have examined the impact of electronic performance monitoring of office workers. This literature suggests that workers under constant electronic monitoring are subject to increased levels of stress, resulting in short-term illness and potential long-term changes in health status. Moreover, organizational and job-related factors impact the effectiveness of this form of employee monitoring. Our discussion of the EPM literature highlighted the importance of the nature of feedback in determining receptiveness to, and effectiveness of, monitoring systems. However, many studies of monitoring systems fail to provide detailed information regarding feedback. Another issue is that studies have tended to focus on individual devices rather than on their underlying features making comparison, and integration, across studies difficult. We argue that one reason for this is that much of this research proceeds without the benefit of an organizing theoretical framework. We describe how one such framework, the Lens Model, that might be used in evaluating the relationships between safety-critical judgments rendered by the system, the driver, and the combination. However, this is just one example of a theoretical framework that could provide guidance to future research on on-board safety devices. Even so, it is clear that the development and use of such frameworks would more rapidly advance our understanding of safety monitoring systems and methods of increasing their effectiveness.

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