Check for updates

John Senders, Human Error, and System Safety

Barry Strauch, Strauch Associates, USA

Objective: I examine John Senders' work and discuss his influence on the study of error causation, error mitigation, and sociotechnical system safety.

Background: John Senders' passing calls for an evaluation of the impact of his work.

Method: I review literature and accident investigation findings to discuss themes in Senders' work and potential associations between that work and error causation and system safety.

Results: Senders consistently emphasized empirical rigor and theoretical exploration in his research, with the desire to apply that work to enhance human performance. He has contributed to changing the way error has been viewed, and to developing and implementing programs and techniques to mitigate error. While a causal relationship between Senders' work and safety cannot be established, an association can be drawn between his research and efforts to mitigate error.

Conclusion: Because of Senders' work, we have a better understanding of error causation and enhanced ways of mitigating system errors. However, new sources of error, involving advanced systems and operators' knowledge and understanding of their functionalities can, if not addressed, degrade system safety.

Application: Modifications to advanced automation and operator training are suggested, and research to improve operator expertise in interacting with automated systems proposed.

Keywords: John Senders, human error, error mitigation, human–automation interaction, accident analysis

INTRODUCTION

John Senders pursued many interests in his lifetime. He began as a lumber yard worker, became a paper mill engineer, and rose to the highest levels of academia. He advised government agencies on policy, earned several patents, provided solutions to "real world" problems, and helped change our understanding of human performance in sociotechnical systems.

Senders was relentless in investigating challenging issues and innovative in conducting research. He developed a device to study driver visual scanning and attention that would, according to preset criteria or driver control, block a driver's visual field to assess his or her knowledge of the immediate environment and ability to apply that knowledge to vehicle control (e.g., Senders et al., 1967). Over 50 years later, ISO continues to use that method and the associated device as a standard to measure visual demand (ISO, 2017). He also developed and was awarded a patent for a device that allows people to retain visual acuity when shifting focus from near to far and far to near, as necessary (Senders, 1980a). Had it been available, it may have prevented an airline accident at New York's LaGuardia Airport in which the captain, at his optometrist's suggestion to compensate for shortcomings in his near and distant vision, wore monovision contact lenses—one correcting for near and the other for distant vision (National Transportation Safety Board, 1997). He incorrectly perceived external visual cues close to the airport and misjudged the airplane's height above the runway on final approach. The airplane struck the edge of the runway and was substantially damaged, fortunately without loss of life.

Senders was so prescient that, in an era of mainframe computers and book- and journal-filled libraries, he accurately predicted a system of digital access to the world's libraries, decades before this was to become a reality (Senders,

Address correspondence to Barry Strauch, Strauch Associates, LLC Annandale, VA 22003, USA; e-mail: bstrauchva@gmail.com

HUMAN FACTORS
Vol. 00, No. 0, Month XXXX, pp. 1-13
DOI:10.1177/00187208211001982
Article reuse guidelines: sagepub.com/journals-permissions
Copyright © 2021, Human Factors and Ergonomics Society.

1983a). He determined the storage requirements of such a system, assuming a constant annual book and journal growth rate (Senders, 1976, 1963). Further, the system he described relied on an internet and affordable and powerful desktop computers, the development of which was decades away.

Senders' career was unusual (Senders & Senders, 2010). He became a senior faculty member at major universities without having an earned doctorate. When he did earn the degree, he based his dissertation on research he had carried out over 30 years earlier (1983b), conducting his doctoral work under the guidance of a faculty member who had himself completed his postdoctoral studies earlier under Senders (Hancock et al., In press).

Senders' initial studies expanded upon the pioneering work of Paul Fitts and his colleagues, which had begun as World War II research to increase military aviation safety (e.g., Fitts & Jones, 1947). Senders expanded considerably on Fitts' work (e.g., Senders, 1953, 1964, Senders, 1966, 1967, 1970, 1997; Senders, Elkind, et al., 1966; Senders et al., 1955). The studies of visual behavior of aircraft pilots that he and his colleagues conducted considerably increased our understanding of the relationship between pilot visual behavior, cognition, and aircraft display design.

Based on that work, Senders (1983b, p. 46) characterized the human operator as "…a single-channel device which is commutated in some aperiodic sequence over a number of (perhaps interrelated) closed loops," a characterization that affords an insight into his view of human performance—and his research. Provided certain conditions are met, the performance of the human operator can be precisely described; enabling one to predict that performance under a variety of factors whose influence can also be measured and evaluated, both mathematically and empirically.

In describing what he perceived to be a shortcoming in Fitts' work, Senders (1983b, p. 11) added

> The approach [Fitts employed] was, therefore, completely empirical: the [pilot] behaviour was to be examined and the [display] design was to be based on the behaviour. Nor was any theory put forward to relate the looking behaviour to what the pilot actually saw on the instrument looked at. What the studies could not do was to enable the investigator to establish rules that would permit generalization of the data to other aircraft, other flight conditions, other maneuvers, or new instruments.

From this, it can be seen that Senders stressed using empirical methodology to examine, expand, or propose theories that could explain and/or predict human performance in multiple systems. He studied pilot behavior, nuclear power facility design, driver behavior, and medical performance, adding to the literature on error mitigation and error causation.

His dedication to studying human performance was such that he did so well outside "typical" research milieus. As his stepdaughter recounted,

> Even being on holiday was an opportunity to apply mathematical models. While sitting by a swimming pool, John explained how the frequency with which a mother has to look at her toddler to ensure it did not end up drowning was based on the toddler's mean velocity, direction, and time since last looking. (Hancock et al., 2019, p. 365).

The appreciation of the value of Senders' many accomplishments is evident from the posthumous tributes to him (e.g., Hancock et al., 2019; in press). In this paper, I examine his work on error causation and mitigation, in recognition of his contribution to sociotechnical system safety.

ERROR CAUSATION

Given Senders' intellectual curiosity, dedication to empiricism, and pursuit of theory, with the desire to use research findings for practical purposes, in hindsight it is not surprising that he would study human error, particularly when he began to do so, around 1980.

To that point, error had largely been examined through research of the type Fitts and his colleagues had pursued, which, as noted, Senders believed lacked a theoretical framework. While there had been earlier studies of error causation (e.g., Fell, 1976), the research was generally atheoretical and its focus was primarily on the error-committing operator(s) (e.g., Alkov et al., 1982), rarely going beyond that person or persons (Coury et al., 2010). For example, in an investigation by the National Transportation Safety Board (1967, p. 1) of a 1967 DC-8 training accident, in which six people on board and 13 on the ground were killed, investigators attributed the accident to the "…improper supervision by the instructor, and the improper use of flight power controls by both the instructor and the captain-trainee during a simulated two-engine out landing approach, which resulted in a loss of control." There was no explanation as to how or why the pilots committed the errors and therefore, no effective means available from the findings to mitigate similar future errors.

Three high-profile sociotechnical system accidents that occurred around this time helped to change this approach: the 1979 Three Mile Island (TMI) and the 1986 Chernobyl nuclear accidents, and the 1984 Bhopal, India, atmospheric release of methyl isocyanate, all initiated or exacerbated by operator errors. Each underscored the need for a theoretical context to study human error. Their collective influence on research into error causation was substantial. As Senders (1983b) noted with regard to the first accident: "Three Mile Island has done more for the field of Engineering Psychology than all the special pleadings of its promoters in the past."

Senders (1980b) was among the first to recognize that error causation was system induced rather than operator induced. While novel at the time, that view is widely accepted today. "…We still need people to oversee the [sociotechnical] systems," he wrote,

> and people often make errors. To solve the problem, designers have tried to design people out of the systems. But it hasn't been possible. Indeed, those who design automated systems to get rid of human errors also make errors themselves. (Senders, 1980b, p. 52)

He followed this early effort with studies into relatively simple errors that subjects made when presented with three-digit numbers (Sellen & Senders, 1986), and later studied the efficacy of failure mode and effects analysis (FMEA) and root cause analysis to explain error causation (Cohen et al., 1994; Senders, 2004). He believed that neither adequately addressed the complexity of factors involved in such causation.

With his then wife, he organized a "clambake conference" (it was held in New England) in 1980 and 3 years later they, with Neville Moray, organized a second and larger one, both of which sought to assess the state of and promote research into human error. Leading researchers from multiple disciplines participated, all sharing a keen interest in error causation. Participants included Jens Rasmussen, Daniel Kahneman, Donald Norman, James Reason, Alan Swain, Thomas Sheridan, Elizabeth Loftus, Eric Hollnagel, and David Woods, all of whom went on to make substantial contributions to our understanding of error, and one, Kahneman, won the Nobel Prize for his work, conducted with the late Amos Twersky, on decision-making and errors in decision-making.

As Senders and Senders (2010) later noted, the conferences "resulted in a change in the way people looked at error." He described them as:

> …a deliberate effort to discover or create an "invisible college" of people interested in working on human error. And I think it succeeded, and I believe it may have had more effect than anything I've been engaged in. Certainly the 1983 conference combined with the first one resulted in a change in the way people looked at error.

Researchers have agreed with his assessment. Hancock et al. (2019, p. 363) described the Clambake Conferences as "seminal foundations for the modern study of error in all its forms." Senders and Moray (1991) text, a product of the conferences, helped guide subsequent error research, articulating much of what is today widely accepted. “If every error has its own unique cause,” they wrote,

> the practical designer of complex systems faces insuperable problems. Each conceivable error would require its own analysis; a remedy for one error would not apply to any other. On the other hand, if there are relatively few causal mechanisms, we can apply some general rules repeatedly, to good effect. (p. 5)

A change to a systems-centered view of error causation, as Senders and Moray (1991) espoused, was not only timely, but logical as well, naturally following Fitts’ research that had demonstrated a link between display design and error. No other suggested approach to error causation before or since could match that of system-centered causation for simplicity, generalizability, and applicability. By all relevant measures, the paradigm Senders and those participating in the Clambake Conferences espoused effectively addressed the study of operator error causation in multiple systems.

This paradigm change led to extraordinarily productive research into error causation. It may be difficult today, some 40 years later, to recognize the value of the conferences because subsequent research has been so fruitful, guiding error studies to this day. “To talk of the cause of errors,” Senders and Moray (1991, p. 29) wrote, “is to talk about the sense in which they can be explained…” Further, “if we have a theory of error and the consequent understanding of its mechanisms,” they wrote (Senders & Moray, 1991, p. 53), “we should be able to minimize the occurrence of errors and mitigate their consequences.” They recognized the difficulty of developing a theory to explain all system errors, and acknowledged that eliminating errors was not realistic. Rather, also consistent with Senders’ perspective on research, they suggested that “…if we can determine when and where an error will occur, and who will commit it, then there is at least the possibility of preventing it….” (Senders & Moray, 1991, p. 59) This perspective on error causation, suggesting the possibility of error mitigation, has become a major objective of subsequent research on error causation.

Senders thereafter conducted error research, among his many endeavors, largely in two settings—automobile driving, a natural follow on to his earlier work on visual occlusion and cognition, and later in medicine, work that continued until shortly before his passing. For example, in examining driver errors and accidents, Green and Senders (2003) applied the system-centered approach advocated in the Clambake Conferences. They wrote that “when a driver fails to avoid an accident because the situation exceeds these limitations, it is often called ‘human error.’ In reality, it is often the situation that is primarily responsible, not the driver’s response to it” (p. 1).

The research he and his colleagues pursued can serve as textbook illustrations of the scientific study of error causation and mitigation. To illustrate, perhaps Senders’ most applied study, an analysis of the likelihood of violating the law while traversing a Toronto intersection, had a unique origin—the report of his son’s colleague of being cited for doing so against a red traffic signal (Senders, 1998). In response to the perceived injustice, Senders timed the duration of the intersection traffic signals and analyzed key vehicle parameters. He found that, even with a green traffic signal, a driver entering the intersection just before it changed to amber would violate the law, regardless of legal vehicle speed. In a classic illustration of his combining the theoretical with the practical, he found that the duration of the amber signal was insufficient to allow drivers to legally traverse the intersection before it turned to red. Consequently, drivers could not have committed errors by attempting to legally traverse the intersection because traffic signal timing rather than driver actions was at fault. Consistent with his stated views on error causation, he argued that the focus on the intersection traffic violations should be on the “system,” in this instance the traffic signals, rather than on the driver. Interestingly, when Senders presented his findings at the individual’s trial, the judge reacted similarly to those with an operator centered focus on error. He refused to consider what he characterized as “all those numbers” and found the driver guilty of violating traffic regulations. In subsequent research, Senders expanded his focus on driving errors, focusing on driver distraction (Hancock et al., 2009; Saffarian et al., 2015; Senders, 2009), a critical safety issue at the time with the advent of smart phones and sophisticated electronic vehicle entertainment systems.

His studies of medical errors led him to suggest simple solutions to mitigate error (e.g., Senders, 1994a). For example, to reduce the likelihood of incorrect medication dose administrations, errors with potentially fatal consequences, Senders and his colleagues applied basic ergonomic principles to demonstrate that modifying package shapes by dosage, added to existing differences in package labeling, would provide sufficient cues to enable health care practitioners to reduce errors in dispensing prepackaged drug syringes of different dosages (Senders, 1994b). Senders later examined errors in communicating prescriptions to pharmacies. Here too he and his colleagues proposed relatively simple solutions to prevent errors in vocally transmitting and aurally receiving medication information, errors also with potentially catastrophic consequences. (Kennedy et al., 2008; Lambert et al., 2010).

Senders similarly studied errors that led to "wrong side surgery," surgery unwittingly performed on the wrong limb or body part such as an arm or leg. As Senders and Kanzki (2008, p. 397) wrote:

> More disturbing … is that so little effort seems to have been made to identify the causes of wrong site surgical error in general, and of wrong side surgical error in particular. If wrong side error was a disease, we would look for its underlying causal mechanism—the "wrong side error virus." That might lead us to ways of curing—that is, eliminating—the error as well as trying to intercept it before it reaches the patient.

After citing error theory and supporting empirical evidence to explain the error's causes, they proposed a relatively simple method to reduce the likelihood of such errors, a pre-surgical protocol in which a nurse, the surgeon, and the patient must each agree on the body part to be the site of the surgery. Of course, even so the authors recognized that each person in the protocol could independently err and identify the same wrong side. As the authors explained, error can be "a random process that springs unaided from the brain" (Senders & Kanzki, 2008, p. 399).

In the four decades since the Clambake Conferences, error causation research that began primarily in nuclear power generation and aviation has been conducted in such systems as mining (Boukas & Kontogiannis, 2019), manufacturing (Marquardt, 2019), marine piloting (National Academy of Sciences, 1994), wildfire response (Brooks et al., 2018), space transportation (Vaughan, 1994), military aviation (Miranda, 2018), response to terrorism (Bye et al., 2019), equipment maintenance and repair (Drury, 1999; Hobbs & Williamson, 2003), and financial trading (Leaver & Reader, 2016), among others. Theoretical and applied research has since addressed such error-related issues as situation awareness (Endsley, 1995), mode awareness in automated systems (Sarter & Woods, 1995), decision-making in dynamic settings (Klein, 1993: Orasanu, 1993), team performance (Salas et al., 2008), and safety culture (Guldenmund, 2000). The research helped to identify error causation patterns that have led to improved error mitigation.

ERROR AND SAFETY

Since the Clambake Conferences, sociotechnical systems have generally gotten safer. In nuclear power generation, for example, the International Atomic Energy Agency's (2020) listing of nuclear incidents showed that all but two in the past 30 years were in facilities other than nuclear-generating ones and those should, more properly, be considered occupational rather than operating incidents. One of the two, a 1993 release of radiation at a spent fuel-reprocessing facility, resulted in few if any adverse environmental or medical consequences. The other was the March 11, 2011, Fukushima Daiichi nuclear facility accident that led to a substantial radioactive release and the permanent evacuation of all persons near the facility. However, its primary cause was not operator error but rather (1) siting and design flaws, that is, siting the facility adjacent to the sea with a relatively small seawall for protection from potential tsunamis, and (2) the absence of reliable sources of backup electrical power after diesel generators flooded following a tsunami (International Atomic Energy Agency, 2015).

In commercial aviation, except for two 2018 and 2019 Boeing 737-Max accidents in Indonesia and Ethiopia, respectively, the safety trend has also been positive. As the insurer Allianz (2019) observed:

> Despite a record number of passengers, statistics show that flying has never been safer. In 2017, for the first time in at least 60 years of aviation, there were no fatalities on a commercial airline. Even 2018, which saw a total of 15 fatal airliner accidents, ranks as the third safest year ever.

The International Air Transport Association (2020, p. 4) likewise found:

> Yearly accident rates indicate a decrease in both the total number of [commercial aircraft] accidents as well as the global accident rate in 2019. The full year 2019 accident rate, which includes all accidents, was 17% lower than that in 2018.

Allianz attributed the safety improvement primarily to technological advances. Improving technology can, of course, reduce opportunities for operator errors resulting from their incorrectly diagnosing and responding to equipment malfunctions.

Highway fatalities in the United States have similarly declined. According to a U.S. government agency, 40,115 people were killed in U.S. highway accidents in 1993, a rate of 15.55 per 100,000 people whereas in 2014, the last year for which data were available, 32,575 were killed, a rate of 10.25 per 100,000 (National Highway Traffic Safety Administration, 2020).

Nevertheless, although sociotechnical system safety has improved, factors other than error mitigation methods may be responsible. With automobiles, for example, greater use of seat belts and both increased enforcement and reduced incidence of impaired driving have contributed to fewer highway fatalities. In commercial aviation, improved aircraft system design and reliability, increased simulator verisimilitude and capabilities, advances in navigation technology, and enhancements to air traffic control aircraft detection hardware and software have all contributed to increased air safety. In nuclear power generation, the accidents at Chernobyl and TMI led to more effective operational oversight and better-designed operator controls and displays.

However, the rarity of sociotechnical system accidents makes determining influences on their causes challenging. Largely because of accident infrequency, studies attempting to link error mitigation programs to safety improvements have been mostly inconclusive. Salas et al. (2001, 2006) and O'Connor et al. (2008), for example, studied the relationship between crew resource management (CRM) and safety, but were unable to establish causal relationships. Grabowski et al. (2010) found relationships between facets of traditional organizational safety culture and what they referred to as leading indicators of safety in marine operations. However, they were unable to establish a relationship between the indicators and accident frequency. The many factors involved make one theory of error causation extraordinarily difficult to propose. Even with a single safety feature, such as safety culture, researchers have been unable to agree on a unified research framework, leading to multiple approaches to error mitigation (Le Coze, 2019).

A CONTEMPORARY SAFETY RISK

The trend of improved sociotechnical system safety will likely continue as technology, training, and knowledge of error causation continue to advance. Nonetheless, unrecognized risks to safety have and will likely continue to be present in systems; anticipating and designing to prevent all potential operator errors is not possible. Particularly as new technology is introduced, opportunities for unrecognized system deficiencies will increase, as occurred with the Boeing

737-Max (House Committee on Transportation and Infrastructure, 2020).

Although unrecognized safety risks may be present in any system, researchers have identified one relatively recent risk, resulting from the multiplicity of automated system functionalities increasingly present in sociotechnical systems. These functionalities call for operator expertise that may exceed that provided for in their training (Strauch, 2017). This should not suggest that Senders' examination of the "fundamentals" of driving, that is, the quantity and type of information drivers obtain visually is no longer relevant. His research contributed substantially to our understanding of technology-related system errors. For example, with Green, he expanded upon his early research on driver performance and observed that "[h]umans have limited information processing abilities and must rely on three fallible mental functions: perception, attention and memory. When a driver fails to avoid an accident [it is] because the situation exceeds these limitations …" (Green & Senders, 2003).

Today, while researchers acknowledge that advanced technology has enhanced safety, they also recognize that it poses safety risks as well (e.g., Jamieson & Vicente, 2005). Automated systems may compensate for cognitive limitations that Green and Senders described, but their capabilities nevertheless depend upon skilled and alert operators to monitor their performance and respond when necessary. Absent that, the risk of error can increase.

Drivers engaging their vehicle automated functionalities may not realize that in so doing demands on their perception, reaction time, attention, and situation awareness are still present, but in ways considerably different from what Senders and Green had examined. Although automated vehicles' functionalities can enhance safety by increasing system robustness to the adverse effects of operator fatigue-, impairment-, and/or medical-related factors, among others that can increase the likelihood of error, (e.g., Casner et al., 2016; Fagnant & Kockelman, 2015; Hancock et al., 2020), they also place monitoring, perceptual, and cognitive demands on drivers that can adversely affect safety if not met.

In these vehicles, sensors and automated functionalities that process sensor input replace operator visual perception to detect road hazards. Sensor failures, such as from design limitations, have led to at least one accident (National Transportation Safety Board (2020a). Natural phenomena, for example, road obscuration from snow and ice, or weather-caused visibility limitations, may also reduce vehicle sensors' ability to accurately recognize lane markers, exit ramp entrances, and the like, reducing their safety capabilities. The mix of potential sensor shortcomings, with possible limitations in the algorithms that integrate sensor input, can lead to operator errors.

Highly automated automobiles can perform some vehicle functions effectively, such as increasing the distance from forward vehicles when thresholds are met, maintaining lateral control and lane position, and navigating along preselected routes. However, what have been called autonomous vehicles are not fully automated; drivers who believe that these vehicles are "self-driving" are mistaken. Rather, they demonstrate relatively low levels of automation. The Society of Automotive Engineers (SAE) has categorized five levels of vehicle automation, of which levels 4 and 5 are considered fully automated, that is, with no continuous operator oversight needed (Society of Automotive Engineers, 2016). By contrast, the autonomous vehicles being sold and operated today achieve, at best, SAE level 2 automation, requiring continuous supervision and monitoring (Shladover, 2016). Even the most advanced vehicles that are offered today require drivers to maintain an ongoing awareness of the operating environment after engaging the automated systems.

Yet, manufacturer and automobile dealers' marketing and communications have influenced drivers to believe that their vehicles' functionalities exceed their actual capabilities (e.g., Abraham et al., 2017; Boelhouwer et al., 2019; Teoh, 2020), in effect encouraging operators to monitor vehicle operations with diminished attention. The chief executive of Tesla, for example, promoted its "autopilot," and promised that the company would be building "self-driving" cars in the near term, that is, within months (Jones, 2019), implying therefore that operator attention to driving would then be unnecessary.

Singer and Jenness (2020), examining automated vehicle driver misconceptions regarding their vehicles' capabilities, showed that the quality of drivers' attention to the road was directly related to the information they had received about automobile capabilities, despite nearly all drivers recognizing the need to continuously monitor their driving. As they found (Singer & Jenness, 2020, p. 1)

> … a branding approach that emphasizes feature capabilities and driver workload reduction—compared to a branding approach that emphasizes feature limitations and driver responsibility—tended to lead to greater confidence in the capabilities of the feature in ways that might lead drivers to over-rely on it or use it unsafely. This result is compounded by a greater likelihood to report willingness to engage in potentially distracting or risky behaviors while driving in the condition that emphasized capabilities.

Supporting this conclusion, the National Transportation Safety Board (2017, 2019, 2020a, 2020b), investigating several automated vehicle accidents, reached a common finding among them; accident drivers were either inattentive throughout the accident sequence or became attentive when it was too late to avoid an accident. Several were texting or had engaged in other smart phone-centered tasks in place of monitoring vehicle performance.

While the proportion of highly automated vehicles among the total number of vehicle accidents is insufficient to draw other than suggestive conclusions (e.g., Dunn et al., 2019; Schoettle & Sivak, 2015), researchers have recognized that although automated features can enhance vehicle safety, they can also detract from safety under certain conditions (e.g., Casner & Hutchins, 2019; Casner et al., 2016; Endsley, 2017; Noy et al., 2018). Further, if engaging automated functionalities (1) precludes inexperienced drivers from gaining operating experience in nonautomated driving, (2) encourages impaired drivers to operate vehicles, and/or (3) engenders unrealistic beliefs regarding their capabilities, driving safety will be compromised. Although he pursued multiple basic and theoretical topics regarding performance in complex systems, Senders did not examine the effects of operator beliefs about, or understanding of, system capabilities on human performance.

Senders demonstrated years ago that even visually occluded drivers can drive safely, provided their situation awareness of immediate road conditions was adequate (Senders et al., 1967). However, the introduction of highly automated vehicles, with manufacturer and dealer misinformation about and driver misunderstanding of their capabilities, has led some operators to rely on vehicle systems rather than their own monitoring for system safety. In effect, they have occluded their own monitoring and thereby lost situation awareness of road conditions. These operators may be unprepared to oversee their systems in critical operating phases. As Singer and Jenness (2020, p. 1) observed, "the safe use of these [automated] systems depends on the driver having an accurate understanding of the capabilities and imitations of the system, including the appropriate driving contexts for the use of the system. …"

Hoffman et al. (2016) highlighted hazards of autonomous weapons systems that make engagement decisions independent of their human supervisors. Those systems have attacked friendly forces, resulting in unintended fatalities. Strauch (2017) argued that the advanced automated systems can lead to what he referred to as the automation-by-expertise-by-training interaction, creating hazards unique to highly automated systems where operator expertise does not meet that required for system operation.

To reduce this risk, designers can present automobile information to make it more intuitive to drivers, employing what is referred to as ecological interface designs. These have been shown to improve operator performance (Vicente, 2002) over standard display formats, a finding related to that of Senders' early work on pilot visual scanning and aircraft display design. Designers can also ensure driver monitoring by such modifications as necessitating continuous tactile contact with controls or control responses to randomly emitted cues. Certainly, drivers need to be fully knowledgeable of and skilled in the automated capabilities and limitations of the vehicles they operate. Because no system has or will likely be designed in the foreseeable future that effectively eliminates the need for human oversight, regulators, manufacturers, designers, trainers, vendors, and others involved in system operations must ensure that operators have the necessary expertise, knowledge, and ability to continuously monitor their systems to enable them to take control when necessary.

Decades ago, Senders (1980b, p. 52) wrote, "we still need people to oversee the systems." Although advanced automated vehicles have become increasingly reliable, what Bainbridge (1983) and Endsley (2017) respectively described as ironies of automation and automation conundrums still holds true; the more capable the automation the less operators will be prepared to respond to system anomalies. Senders' belief in the need for human supervisory control of sociotechnical systems should remain valid for some time.

Regulators, recognizing the risk to safety, have attempted to address these technological advances. Government agencies, such as the National Highway Traffic Safety Administration (2017) and the United Nations Economic Commission for Europe (UNECE, 2019) have each issued guidance on regulating advanced automated vehicles. Similarly, German researchers have proposed guidance for automated lane keeping systems (UNECE, 2020).

To effectively integrate automated capabilities with those of their human supervisors, designers, trainers, regulators, and all who play a role in system operations should address limitations of both operators and automation to maximize system performance. Overlooking or minimizing the role of the operator or the information the operator needs for system operation jeopardizes system safety. So long as operators are cognizant of and understand system limitations and capabilities, and are skilled in their operation, highly automated systems can continue to improve system safety. Otherwise, the automation by training by expertise interaction will continue to detract from it.

LIMITATIONS AND CONCLUSIONS

I did not have the good fortune to meet John Senders; I knew him only from his work and through others who had known or worked with him. He was an extraordinary person, with a nearly insatiable intellectual curiosity and the willingness to address many of the critical issues of our time. The research he conducted inspired many. While some may draw different conclusions about his work and his impact on error research and system safety than I have, it is difficult to consider error causation and system safety today without acknowledging Senders' considerable contributions to these fields.

In 1991, with Neville Moray, he wrote (Senders & Moray, 1991, p. 6):

> Even if we do not know when an error will occur, can we predict what form it may take? This question obviously has tremendous implications for system design. It might be possible to erect defenses that would prevent a least some errors from happening. Such defenses could create a trade-off in which other, less undesirable errors become more likely. Alternatively, machines and systems could be designed to "absorb" the errors that would be made.

The thrust of these words, drawn from the Clambake Conferences, has, perhaps more than most of Senders' work, influenced error research. Identifying and implementing defenses against error has been a focus of sociotechnical system design and operation for some time. Therefore, in considering Senders' legacy, rather than examining the relationship between Senders' research and safety, a more productive approach would be to consider the extent to which he has contributed to identifying and mitigating system shortcomings that can lead to error. He has clearly done so, especially in medicine, driving, aviation, and nuclear power generation, while influencing others to do the same in these and other systems.

Senders helped initiate empirical research into error causation, and was among many whose research has led to the increased understanding of the role of system design and oversight in operator error causation. His efforts to promote such research helped precipitate productive studies that followed, but it cannot be stated conclusively that absent his work the error causation paradigm that has influenced error research would not have changed to a system-centered one, and our understanding of error causation would not have been achieved. Nonetheless, I argue that his call for research, the influence of his studies, his mentoring and encouragement of others, all contributed to that paradigm shift.

Future research should be conducted to enhance our understanding of error. This research will likely increase our understanding of error causation and lead to improvements in its mitigation. Senders likely would have welcomed these outcomes, provided they resulted from empirically sound research. Expanding our knowledge of human performance and system safety was a major objective of his life's work.

While the totality of advances in system safety today is likely due to a variety of factors, Senders provided a foundation for our current understanding of the causes of error and their relationship to safety. Through his work, he showed that errors could and should be mitigated, and that system safety needed research to identify and address errors that threatened it. His efforts to understand error causation and suggest ways to mitigate error risk, among his many achievements, stand among the major accomplishments of our time.

ACKNOWLEDGMENTS

I thank three anonymous reviewers whose constructive comments led to a considerably improved manuscript.

KEY POINTS

- John Senders helped to initiate the formal study of human error causation, following a series of high profile sociotechnical system accidents, in a time when error research largely focused on the operator who committed the error, rather than on the system in which the error occurred.
- The scientific study of error after major sociotechnical system accidents had occurred led to improved investigative focus on operating system design and to techniques designed to mitigate risks of error.
- Improved system safety has been seen in several sociotechnical systems, but establishing a causal relationship between error research and system safety is difficult.
- The implementation of advanced automated functionalities in sociotechnical systems, while contributing to enhanced safety, has also increased some risks to safety.
- John Senders' work in understanding error causation and developing mitigation techniques has helped to influence subsequent researchers to identify and suggest error mitigation methods in several sociotechnical systems.

ORCID iD

Barry Strauch https://orcid.org/0000-0003-4928-3120

REFERENCES

Abraham, H., McAnulty, H., Mehler, B., & Reimer, B. (2017). Case study of today's automotive dealerships: Introduction and delivery of advanced driver assistance systems. *Transportation Research Record: Journal of the Transportation Research Board*, *2660*, 7–14. https://doi.org/10.3141/2660-02

Alkov, R. A., Borowsky, M. S., & Gaynor, J. A. (1982). Stress coping and the U.S. navy aircrew factor mishap. *Aviation Space and Environmental Medicine*, *53*, 1112–1115.

Allianz. (2019). *Aviation risk 2020: Safety and the state of the nation*. Allianz Global Corporate & Specialty. https://www.agcs.allianz.com/news-and-insights/reports/aviation-risk-report.html.

Bainbridge, L. (1983). Ironies of automation. *Automatica*, *19*, 775–779. https://doi.org/10.1016/0005-1098(83)90046-8

Boelhouwer, A., van den Beukel, A. P., van der Voort, M. C., & Martens, M. H. (2019). Should I take over? Does system knowledge help drivers in making take-over decisions while driving a partially automated car? *Transportation Research Part F: Traffic Psychology and Behaviour*, *60*, 669–684. https://doi.org/10.1016/j.trf.2018.11.016

Boukas, D., & Kontogiannis, T. (2019). A system dynamics approach in modeling organizational tradeoffs in safety management. *Human Factors and Ergonomics in Manufacturing & Service Industries*, *29*, 389–404. https://doi.org/10.1002/hfm.20795

Brooks, B., Curnin, S., Bearman, C., & Owen, C. (2018). Human error during the multilevel responses to three Australian bushfire disasters. *Journal of Contingencies and Crisis Management*, *26*, 440–452. https://doi.org/10.1111/1468-5973.12221

Bye, R. J., Almklov, P., Antonsen, S., Nyheim, O. M., Aalberg, A. L., & Johnsen, S. O. (2019). The institutional context of crisis. A study of the police response during the 22 July terror attacks in Norway. *Safety Science*, *111*, 67–79. https://doi.org/10.1016/j.ssci.2018.09.011

Casner, S. M., & Hutchins, E. L. (2019). What do we tell the drivers? Toward minimum driver training standards for partially automated cars. *Journal of Cognitive Engineering and Decision Making*, *13*, 55–66. https://doi.org/10.1177/1555343419830901

Casner, S. M., Hutchins, E. L., & Norman, D. (2016). The challenges of partially automated driving. *Communications of the ACM*, *59*, 71–77. https://doi.org/10.1145/2830565

Cohen, M. R., Senders J, W., & Davis, N. M. (1994). Failure mode and effects analysis: Dealing with human error. *Nursing*, *24*, 40.

Coury, B. G., Ellingstad, V. S., & Kolly, J. M. (2010). Transportation accident investigation: The development of human factors research and practice. *Reviews of Human Factors and Ergonomics*, *6*, 1–33. https://doi.org/10.1518/155723410X12849346788624

Drury, C. G. (1999). Human factors in aviation maintenance. In D. J. Garland, J. A. Wise, & V. D. Hopkins (Eds.), *Handbook of aviation human factors* (pp. 591–606). Lawrence Erlbaum Associates.

Dunn, N., Dingus, T., & Soccolich, S. (2019). *Understanding the impact of technology: Do advanced driver assistance and semi-automated vehicle systems lead to improper driving behavior?* AAA Foundation to Traffic Safety. https://aaafoundation.org/wp-content/uploads/2019/12/19-0460_AAAFTS_VTTI-ADAS-Driver-Behavior-Report_Final-Report.pdf.

Endsley, M. R. (1995). Toward a theory of situation awareness in dynamic systems. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *37*, 32–64. https://doi.org/10.1518/001872095779049543

Endsley, M. R. (2017). From here to autonomy: Lessons learned from human–automation research. *Human Factors*, *59*, 5–27. https://doi.org/10.1177/0018720816681350

Fagnant, D. J., & Kockelman, K. (2015). Preparing a nation for autonomous vehicles: Opportunities, barriers and policy recommendations. *Transportation Research Part A: Policy and Practice*, *77*, 167–181. https://doi.org/10.1016/j.tra.2015.04.003

Fell, J. C. (1976). A motor vehicle accident causal system: The human element. *Human Factors*, *18*, 85–94. https://doi.org/10.1177/001872087601800109

Fitts, P. M., & Jones, R. E. (1947). Analysis of factors contributing to 460 “pilot-error” experiences in operating aircraft controls (AMC Memorandum Rep. TSEAA.694.12A). Air Materiel Command. https://apps.dtic.mil/dtic/tr/fulltext/u2/a800143.pdf

Grabowski, M., You, Z., Wang, H., & Merrick, J. R. W. (2010). *Sailing on Friday: Developing the link between safety culture and performance in safety-critical systems*. (Vol. 40, pp. 263-284). IEEE Transactions on Systems, Man, and Cybernetics, Part A.

Green, M., & Senders, J. (2003). Human error in road accidents. Washington, DC: transportation research information service (accession number: 00943796). http://visualexpert.com/Resources/roadaccidents.html

Guldenmund, F. W. (2000). The nature of safety culture: A review of theory and research. *Safety Science*, *34*, 215–257. https://doi.org/10.1016/S0925-7535(00)00014-X

Hancock, P. A., Crichton-Harris, A., Sellen, A., Sheridan, T. B., & Hancock, G. M. (In press). A distracted scientist: The life and contributions of John Senders. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 001872082094197. https://doi.org/10.1177/0018720820941970

Hancock, P. A., Hancock, G. M., Senders, W., & Sellen A. J. (2019). John Senders (1920–2019). *The American Journal of Psychology*, *132*, 361–367. https://doi.org/10.5406/amerjpsyc.132.3.0361

Hancock, P. A., Kajaks, T., Caird, J. K., Chignell, M. H., Mizobuchi, S., Burns, P. C., Feng, J., Fernie, G. R., Lavallière, M., Noy, I. Y., Redelmeier, D. A., & Vrkljan, B. H. (2020). Challenges to human drivers in increasingly automated vehicles. *Human Factors*, *62*, 310–328. https://doi.org/10.1177/0018720819900402

Hancock, P. A., Mouloua, M., & Senders, J. W. (2009). On the philosophical foundations of the distracted driver and driving distraction. In M. A. Regan, J. D. Lee, & K. Young (Eds.), *Driver distraction: Theory, effects, and mitigation* (pp. 11–30). CRC Press.

Hobbs, A., & Williamson, A. (2003). Associations between errors and contributing factors in aircraft maintenance. *Human Factors*, *45*, 186–201. https://doi.org/10.1518/hfes.45.2.186.27244

Hoffman, R. R., Cullen, T. M., & Hawley, J. K. (2016). The myths and costs of autonomous weapon systems. *Bulletin of the Atomic Scientists*, *72*, 247–255. https://doi.org/10.1080/00963402.2016.1194619

House Committee on Transportation and Infrastructure. (2020). Final Committee Report: The Design, Development & Certification of the Boeing 737 Max. (September). https://transportation.house.gov/imo/media/doc/2020.09.15%20FINAL%20737%20MAX%20Report%20for%20Public%20Release.pdf

International Air Transport Association. (2020). Safety report 2019 (Edition 56). https://www.iata.org/en/publications/safety-report/

International Atomic Energy Agency. (2015). *The Fukushima Daiichi accident: Report by the director General*. https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1710-ReportByTheDG-Web.pdf.

International Atomic Energy Agency. (2020). Nuclear and radiological accident reports. https://www.iaea.org/search/google/radiological%20accidents

ISO. (2017). *ISO 16673 Road vehicles—Ergonomic aspects of transport information and control systems—Occlusion method to assess visual demand due to the use of in-vehicle systems*. International Organization for Standardization.

Jamieson, G. A., & Vicente, K. J. (2005). Designing effective human-automation-plant interfaces: A control-theoretic perspective. *Human Factors*, *47*, 12–34. https://doi.org/10.1518/0018720053653820

Jones, C. (2019). Tesla’s Musk is overpromising again on self-driving cars. Forbes. https://www.forbes.com/sites/chuckjones/2019/10/22/teslas-musk-is-overpromising-again-on-self-driving-cars/#285669575e98

Kennedy, A. G., Littenberg, B., & Senders, J. W. (2008). Using nurses and office staff to report prescribing errors in primary care. *International Journal for Quality in Health Care*, *20*, 238–245. https://doi.org/10.1093/intqhc/mzn015

Klein, G. A. (1993). A recognition-primed decision (RPD) model of rapid decision making. In G. A. Klein, J. Orasanu, R. Calderwood, & C. E. Zsambok (Eds.), *Decision Making in Action: Models and methods* (pp. 138–147). Ablex.

Lambert, B. L., Dickey, L. W., Fisher, W. M., Gibbons, R. D., Lin, S.-J., Luce, P. A., McLennan, C. T., Senders, J. W., & Yu, C. T. (2010). Listen carefully: The risk of error in spoken medication orders. *Social Science & Medicine*, *70*, 1599–1608. https://doi.org/10.1016/j.socscimed.2010.01.042

Le Coze, J. C. (2019). How safety culture can make us think. *Safety Science*, *118*, 221–229. https://doi.org/10.1016/j.ssci.2019.05.026

Leaver, M., & Reader, T. W. (2016). Human factors in financial trading: An analysis of trading incidents. *Human Factors*, *58*, 814–832. https://doi.org/10.1177/0018720816644872

Marquardt, N. (2019). Situation awareness, human error, and organizational learning in sociotechnical systems. *Human Factors and Ergonomics in Manufacturing & Service Industries*, *29*, 327–339. https://doi.org/10.1002/hfm.20790

Miranda, A. T. (2018). Understanding human error in naval aviation mishaps. *Human Factors*, *60*, 763–777. https://doi.org/10.1177/0018720818771904

National Academy of Sciences. (1994). *Minding the Helm: Marine Navigation and Piloting*. National Academy Press.

National Highway Traffic Safety Administration. (2017). Automated driving systems 2.0, a vision for safety. https://www.nhtsa.gov/sites/nhtsa.dot.gov/files/documents/13069a-ads2.0_090617_v9a_tag.pdf

National Highway Traffic Safety Administration. (2020). Traffic safety facts 1993. https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/93F9;

National Transportation Safety Board. (1967). *Aircraft Accident Report, Delta Air Lines Inc., Dc-8, N203e, Kenner, Louisiana, March 30, 1967*. https://www.ntsb.gov/investigations/AccidentReports/Reports/AAR67AG.pdf.

National Transportation Safety Board. (1997). Aircraft accident report, descent below visual glidepath and collision with terrain, delta air lines flight 554, McDonnell Douglas MD-88, N914DL, LaGuardia Airport, New York, October 19, 1996 (NTSB/AAR-

97/03). https://www.ntsb.gov/investigations/AccidentReports/Reports/AAR9703.pdf

National Transportation Safety Board. (2017). Highway accident report, collision between a car operating with automated vehicle control systems and a tractor-semitrailer truck, near Williston, Florida, May 7, 2016, (NTSB/HAR-17/02). https://www.ntsb.gov/investigations/AccidentReports/Reports/HAR1702.pdf

National Transportation Safety Board. (2019). Highway accident report, collision between vehicle controlled by developmental automated driving system and pedestrian, Tempe, Arizona, March 18, 2018 (NTSB/HAR-19/03). https://www.ntsb.gov/investigations/AccidentReports/Reports/HAR1903.pdf

National Transportation Safety Board. (2020a). Highway accident brief, collision between CAR operating with partial driving automation and truck-tractor semitrailer, Delray beach, Florida, March 1, 2019. (NTSB/ NTSB/HAB-20/01). https://www.ntsb.gov/investigations/AccidentReports/Reports/HAB2001.pdf

National Transportation Safety Board. (2020b). Highway accident report, collision between a sport utility vehicle operating with partial driving automation and a crash attenuator, mountain view, California March 23, 2018. (NTSB/HAR-20/01). https://www.ntsb.gov/investigations/AccidentReports/Reports/HAR2001.pdf

Noy, I. Y., Shinar, D., & Horrey, W. J. (2018). Automated driving: Safety blind spots. *Safety Science*, *102*, 68–78. https://doi.org/10.1016/j.ssci.2017.07.018

O'Connor, P., Campbell, J., Newon, J., Melton, J., Salas, E., & Wilson, K. A. (2008). Crew resource management training effectiveness: A meta-analysis and some critical needs. *The International Journal of Aviation Psychology*, *18*, 353–368. https://doi.org/10.1080/10508410802347044

Orasanu, J. M. (1993). Decision-making in the cockpit. In E. L. Wiener, B. G. Kanki, & R. L. Helmreich (Eds.), *Cockpit resource management* (pp. 137–172). Academic Press.

Saffarian, M., de Winter, J. C. F., & Senders, J. W. (2015). Measuring drivers' visual information needs during braking: A simulator study using a screen-occlusion method. *Transportation Research Part F: Traffic Psychology and Behaviour*, *33*, 48–65. https://doi.org/10.1016/j.trf.2015.07.001

Salas, E., Burke, C. S., Bowers, C. A., & Wilson, K. A. (2001). Team training in the skies: Does crew resource management (CRM) training work? *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *43*, 641–674. https://doi.org/10.1518/001872001775870386

Salas, E., Cooke, N. J., & Rosen, M. A. (2008). On teams, teamwork, and team performance: Discoveries and developments. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *50*, 540–547. https://doi.org/10.1518/001872008X288457

Salas, E., Wilson, K. A., Burke, C. S., & Wightman, D. C. (2006). Does crew resource management training work? An update, an extension, and some critical needs. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *48*, 392–412. https://doi.org/10.1518/001872006777724444

Sarter, N. B., & Woods, D. D. (1995). How in the world did we ever get into that mode? Mode error and awareness in Supervisory control. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *37*, 5–19. https://doi.org/10.1518/001872095779049516

Schoettle, B., & Sivak, M. (2015). A preliminary analysis of real-world crashes involving self-driving vehicles (Report No. UMTRI-2015-34). The University of Michigan Transportation Research Institute. http://umich.edu/~umtriswt/PDF/UMTRI-2015-34.pdf

Senders, J. W. (1953). *The influence of surround on tracking performance, part 1. tracking on combined pursuit and compensatory one-dimensional tasks with and without a structured surround, (WADC technical report 52-229*. Wright Air Development Center, Air Research and Development Command.

Senders, J. W. (1963). Information storage requirements for the contents of the world's libraries. *Science*, *141*, 1067–1068. https://doi.org/10.1126/science.141.3585.1067

Senders, J. W. (1964). The human operator as a monitor and controller of multidegree of freedom systems. *IEEE Transactions on Human Factors in Electronics*, *HFE-5*, 2–5. https://doi.org/10.1109/THFE.1964.231647

Sellen, A. J., & Senders, J. W. (1986). *At least some errors are randomly generated (Freud was wrong)*. Paper presented at the Twenty-First Annual Conference on Manual Control (Report CP 2428). NASA Ames Research Center

Senders, J. (1976). The scientific journal of the future. *The American sociologist*, *11*, 160–164.

Senders, J. W. (1970). The estimation of operator workload in complex systems. In K. B. DeGreene (Ed.), *Psychological factors in systems* (pp. 207–215). McGraw-Hill.

Senders, J. W. (1980a). Vision compensation (U.S. patent 4,181,408). U.S. patent and Trademark office. http://patft.uspto.gov/netacgi/nph-Parser?Sect1=PTO2&Sect2=HITOFF&p=1&u=%2Fnetahtml%2FPTO%2Fsearch-bool.html&r=1&f=G&l=50&co1=AND&d=PTXT&s1=%22vision+compensation%22.TI.&s2=4,181,408.PN.&OS=TTL/

Senders, J. W. (1980b). Is there a cure for human error? *Psychology Today*, *13*, 52–62.

Senders, J. W. (1983a). I have seen the future, and it doesn't work: The electronic journal experiment. *Computer Compacts*, *1*, 31–33. https://doi.org/10.1016/0167-7136(83)90121-X

Senders, J. W. (1983b) *Visual sampling processes*. Unpublished doctoral Dissertation: Tilburg University

Senders, J. W. (1994b). Medical devices, medical errors, and medical accidents. In M. S. Bogner (Ed.), *Human error in medicine* (pp. 159–177). Lawrence Erlbaum Associates.

Senders, J. W. (1997). Distribution of visual attention in static and dynamic displays. *Proceedings of SPIE*, *3016*, 186–194.

Senders, J. W. (1998). Analysis of an intersection. *Ergonomics in Design*, *6*, 4–6.

Senders, J. W. (1994a). Detecting, correcting, and interrupting errors. *Journal of Intravenous Nursing*, *18*, 28–32.

Senders, J. W. (1966). A Re-analysis of the pilot eye-movement data. In *IEEE transactions on human factors in electronics* (Vol. HFE-7, pp. 103–106). https://doi.org/10.1109/THFE.1966.232330

Senders, J. W. (1967). On the distribution of attention in a dynamic environment. *Acta Psychologica*, *27*, 349–354. https://doi.org/10.1016/0001-6918(67)90079-0

Senders, J. W. (2004). FMEA and RCA: The mantras of modern risk management. In *Quality and safety in health care* (Vol. 13, pp. 249–250). https://doi.org/10.1136/qshc.2004.010868

Senders, J. W. (2009). *Driver distraction and inattention: A queuing theory approach*. Paper presented at the 1st International Conference on Driver Distraction and Inattention: (DDI 2009). September 28-29, 2009, Gothenburg, Sweden.

Senders, J. W., Elkind, J. I., Grignetti, M. C., & Smallwood, R. (1966). *An investigation of the visual sampling behaviour of human observers* (Report No. CR 434): NASA Langley Research Center. Retrieved from https://ntrs.nasa.gov/search.jsp?R=19660013621.

Senders, J. W., & Kanzki, R. (2008). The egocentric surgeon or the roots of wrong side surgery. *Quality & Safety in Health Care*, *17*, 396–400. https://doi.org/10.1136/qshc.2007.023564

Senders, J. W., Kristofferson, A. B., Levison, W. H., Dietrich, C. W., & Ward, J. L. (1967). The attentional demand of automobile driving. *Highway Research Record*, *195*, 15–32.

Senders, J. W., & Moray, N. P. (1991). *Human error: Cause, prediction, and reduction*. Lawrence Erlbaum Associates.

Senders, J. W., & Senders, W. (2010). Autobiographical notes. http://www.johnwsenders.net/autobio/

Senders, J. W., Webb, I. B., & Baker, C. A. (1955). The peripheral viewing of dials. *Journal of Applied Psychology*, *39*, 433–436. https://doi.org/10.1037/h0045905

Shladover, S. E. (2016). The truth about "self-driving" cars. *Scientific American*, *314*, 52–57. https://doi.org/10.1038/scientificamerican0616-52

Singer, J., & Jenness, J. W. (2020). *Impact of information on consumer understanding of a partially automated driving system*. AAA Foundation for Auto Safety.

Society of Automotive Engineers. (2016). *Taxonomy and definitions for terms related to driving automation systems for on-road motor vehicles (standard J3016_201806)*. SAE International. https://doi.org/10.4271/j3016_201609

Strauch, B. (2017). The automation-by-expertise-by-training interaction: Why automation-related accidents continue to occur in sociotechnical systems. *Human Factors*, *59*, 204–228.

Teoh, E. R. (2020). What's in a name? Drivers' perceptions of the use of five SAE level 2 driving automation systems. *Journal of Safety Research*, *72*, 145–151. https://doi.org/10.1016/j.jsr.2019.11.005

UNECE. (2019). Global forum for road traffic safety (WP.1): Resolution on the deployment of highly and fully automated vehicles in road traffic. https://www.unece.org/fileadmin/DAM/trans/main/wp1/wp1doc/WP1_Resolution_Brochure_EN_web.pdf

UNECE. (2020). Proposal for amendments to UN regulation on automated Lane keeping system (ALKS) (Report No. ECE/TRANS/WP.29/GRVA/2020/33). Retrieved from https://www.unece.org/fileadmin/DAM/trans/doc/2020/wp29grva/ECE-TRANS-WP29-GRVA-2020-33e.pdf.

Vaughan, D. (1994). *The Challenger launch decision*. University of Chicago Press.

Vicente, K. J. (2002). Ecological interface design: Progress and challenges. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *44*, 62–78. https://doi.org/10.1518/0018720024494829

Barry Strauch is the principal of Strauch Associates, LLC, a consulting organization focusing on human error and transportation safety. He retired from the National Transportation Safety Board after 33 years of service as an investigator and supervisory investigator focusing on human factors investigations and training in investigative procedures and human factors. He earned a PhD in educational psychology in 1975 from Pennsylvania State University.

Date received: April 24, 2020
Date accepted: February 19, 2021