Issues in the Evaluation of Driver Distraction Associated with In-Vehicle Information and Telecommunications Systems

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Abstract

The evaluation of in-vehicle information and telecommunications systems from the standpoint of driver distraction is of great importance to highway safety and the successful deployment of the Intelligent Transportation Systems (ITS) initiative. In this paper, several issues are discussed that bear upon the evaluation of distraction associated with such systems are discussed. The range of distraction phenomena that should be examined are described. The measures commonly used to assess such demands are mentioned. The issue of incidence of use is introduced with a numerical example to illustrate its importance in estimating the safety impact of a technology. The hazard analysis approach to predicting safety impacts in terms of crash counts is discussed, again with a numerical example showing potential pitfalls of restricting attention to "near miss" data only. Finally, the prospects of building a solid case for the importance of driver distraction on highway safety is discussed by drawing an analogy with research into the link between smoking and cancer.

Introduction

The Intelligent Transportation Systems (ITS) initiative has produced a wide variety of in-vehicle driver information systems. At the same time, telecommunications device use (i.e., cellular telephones) while driving has virtually exploded. This brave new world offers the 21st century driver with many potential benefits. Increased productivity is a pressing national goal as people find themselves spending long periods of time engaged in the seemingly monotonous task of driving. ITS products and services can make long commutes more an opportunity to complete useful pursuits and less a matter of 'lost time.'

The benefits of ITS are among the reasons government and industry are seeking to develop this technology. Yet concern exists that such devices may introduce unprecedented levels of driver distraction, either singly or in combination. The purpose of this paper is to examine some key issues associated with the safety evaluation of in-vehicle information and telecommunications systems, specifically in the context of driver distraction. The variety of distraction phenomena that should be evaluated is discussed. The measures commonly used to assess such demands are described. The issue of incidence of use is introduced with a numerical example to illustrate its importance. The hazard analysis approach to predicting safety impacts in terms of crash counts is discussed, again with a numerical example. Finally, the prospects of building a solid case for the importance of driver distraction on highway safety is discussed by drawing an analogy with research into the link between smoking and cancer.

Varieties of Driver Distraction

Driver distraction can manifest itself in several ways (Brown, 1994). A general withdrawal of attention manifests itself in both degraded vehicle control and degraded object and event detection. The putative mechanisms behind this are eyelid closure (in the case of driver fatigue) or eye glances away from the road scene (in the case of visual inattention). A second, and more insidious, type of distraction is what is termed the selective withdrawal of attention. In this type of distraction, vehicle control (e.g., lanekeeping, speed maintenance) remains largely unaffected but object and event detection is degraded. The putative mechanism behind this is attention to thoughts and might be indicated by open-loop rather than closed-loop visual scanning, restricted visual sampling of mirrors and the road scene, empty field myopia (e.g., fixating too close), and selective filtering of information based on expectations rather than the actual situation. These categories of driver distraction suggest different types of measures and scenarios for evaluation of their presence during device use. For example, measurement of lanekeeping performance represents an example of general withdrawal of attention but says nothing about the selective withdrawal of attention that might be associated with a device that perhaps does not require a visual resource, e.g., a voice-recognition system.

There is also a type of distraction effect which I term biomechanical interference. This refers to body shifts out of the neutral seated position, e.g., when reaching for a cellular telephone or leaning over to see or manipulate a device. That this may be important is indicated by a recent report from the Japan that indicated the preponderance of cellular telephone-related crashes were associated with receiving calls and reaching for the cell phone (National Police Agency of Japan, 1998). Similarly, the hand(s) occupied and off the steering wheel might degrade the driver's ability to execute maneuvers. These types of manual loads might involve, e.g., operating a hand-held remote for a route guidance system, a hand-held cellular telephone, eating, drinking, lighting a cigarette, etc. These are the types of biomechanical interference effects that a thorough safety evaluation should also be prepared to address.

Device Demand Measures

Except perhaps in retrospect, safety cannot be measured directly (Dingus, 1997). Indirect measures which are used to measure safety-relevant distraction effects can be put into several categories (Tijerina, Kiger, Rockwell, and Wierwille, 1996). Driver eye glance behavior measures are taken primarily because of the importance of vision in driving. Glance durations, glance frequency, and scanning patterns are part of this set of measures. Driver-vehicle performance measures are also popular because of their *prima facie* safety relevance. Lanekeeping, speed maintenance, car following performance, and driver reaction times to objects and events are common measures from this class. Driver control actions such as steering wheel inputs, accelerator modulations, gear shifting, brake pedal applications, and hand-off-wheel time all have been or can be used to make inferences about the distraction level a driver is under during a trial. Subjective assessments of driver workload and device design are also sometimes used. Finally, measures of the in-vehicle task such as task completion time have been used or are being proposed as a index of the distraction potential of a device (Green, 1998).

It is interesting to note that a measure such as the number of lane exceedences during device use is not considered *prima facie* safety-relevant by everyone. For example, some argue that if there is no one nearby, if the lane exceedence is small or of short duration, if the lane exceedence reflects the driver's strategy for reducing workload during concurrent task execution....there is no safety implication at all. This is an intriguing line of reasoning. On the one hand, it honors the wisdom of the driver to generally make good choices. On the other hand, it flies in the face of accident statistics that indicate drivers by and large get into trouble precisely when they think everything is fine, i.e., in daytime, dry pavement, moderate traffic density situations (Wiacek and Najm, 1999). At present, it seems ill-advised to run a comparative study of different devices or tasks, find that one generates substantially more lane exceedences, yet declare such results irrelevant unless there happened to be a near miss. Tijerina (1996) pointed out that the chaotic nature of crash occurrence may be taken to imply that new technology that taken the driver's eyes off the road or attention away from the driving task produces an incremental rise the crash hazard exposure.

Incidence of Device Use and Highway Safety

Together with in-vehicle task demand, the incidence of task execution is critical to safety evaluations and safety benefits estimation. To illustrate this point, consider hands-free cellular telephone operation as a hypothetical example. Goodman, Tijerina, and Bents (1998) point out that there are several legislative initiatives to mandate hands-free phones as a traffic safety enhancement. However, the increased ease of use that might accompany hands-free operation might also increase the incidence of cellular phone use while driving. Drivers who previously used hand-held units might use their cellular phones more frequently. They may use the cell phone over a broader range of speed regimes, road types, and driving situations (dense traffic, bad weather, through intersections, etc.). Drivers who previously would not have used the cellular phone while driving might now begin to do so because of the perception that hands-free operation is "safe." Drivers might engage in longer voice communications with hands-free units now that they do not have to hold the phone to their ears. That such driver adaptations can have significant safety implications is illustrated below.

In this example, assume there are N = 1,000,000 cellular telephone users who use the cellular telephone while driving (at least occasionally). Of these, $n_{hand\text{-}held}$ = 900,000 use a hand-held phone and $n_{hands\text{-}free}$ = 100,000 use a hands-free cell phone. The hypothetical crash record indicates that there are $N_{crashes}$ = 1000 police-reported cellular-telephone-related crashes in a baseline year. Of these, $n_{crash}(hand\text{-}held)$ = 960 crashes involve hand-held phones and

n_{crash}*(hands-free)* = 40 involve hands-free phones. Given these hypothetical data, one can calculate relative-frequency estimates of crash probabilities for hands-free and hand-held cell phone use while driving:

$$\hat{p}_{Crash}(Hand-Held) = n_{crash}(hand-held)/n_{hand-held}$$
$$= 960/900000 = 0.00107$$

$$\hat{p}_{Crash}(Hands-Free) = n_{crash}(hands-free)/n_{hands-free}$$
$$= 40/100000 = 0.0004$$

Taking the ratio of these two probability estimates indicates that hands-held technology is a factor of 2.68 safer than hand-held technology. If one looks no further, it appears that hands-free units have an indisputable safety benefit and should be made mandatory if cellular telephones are used while driving.

Next, assume that hands-free phones have become quite popular and are even legislated in many states. Now, there are *N'* = 2,000,000 cellular telephone users who use the cellular telephone while driving (but the number of drivers has remained the same). Of these, 0.5 million continue to use hand-held units, while the remaining 1.5 million use hands-free units. Based on the previous crash statistics, the estimated number of crashes, $N'_{crashes}$ is:

$$N'_{Crashes} = p_{crash}(Hand-held)(n_{hand-held}) + p_{crash}(Hands-Free)(n_{hands-free})$$
$$= (0.00107(500000) + (0.0004)(1500000) = 1135 \text{ crashes}$$

Despite no increase in the number of drivers (only the number of drivers who use cellular telephones while driving), the number of cellular-phone related crashes has increased 13.5% since the wide-scale introduction of hands-free phones, a safety-relevant technology that empirical data had indicated should be safer than hand-held operation by a substantial margin.

The solution to this safety problem, one might surmise, would be to have only hands-free cellular phones. Indeed, the migration of the half-million hand-held cell phone users to hands-free phones would result in a reduction in the estimated number of related crashes to 800, a 20% decrease from the baseline. But the hypothesis that increased ease-of-use prompts greater use suggests that the number of hands-free users would continue to rise over time as well. It is easy to verify that the breakpoint for no change in crashes from the baseline of 1000 per year is reached if the number of hands-free phone users increases to 2.5 million in this example. The crash incidence starts going above the baseline if the number of hands-free phone users climbs still higher. The point of the example is that a comprehensive safety evaluation should consider both the demand when a device is used, and also the incidence of device use. The latter has been woefully overlooked in highway safety research for many years.

Hazard Analysis and the Traffic Conflict Technique in ITS Safety Evaluation

There has been great interest of late in the estimation of safety benefits and disbenefits associated with safety-relevant technology in general and ITS technology in particular. One approach that has been suggested to estimate the safety consequences of in-vehicle information systems is the hazard analysis approach (Dingus, 1997). This method, in turn, is based on the Traffic Conflicts Technique (TCT) (Older and Spicer, 1976). The logic of the hazard analysis approach is seemingly straightforward. Crashes are rare events and this makes crash counts impractical for predictive safety evaluations. On the other hand, there exists a hierarchy of 'incidents' (observable events or situations to be described shortly) that occur more frequently. It is assumed that there is a relationship between these 'incidents' and crashes. The logic for safety research, then, is to measure the more frequently occurring incidents in small-scale (of duration, size, or both) evaluations, and extrapolate to estimate the rare events (crashes) to arrive at safety estimates. Thus, the number of crashes expected with a device for a given time period equals the number of incidents observed with that device during a time period times and the crash-to-incident ratio for that device.

To illustrate some of the problems associated with this approach, consider the data in Table 1. The first two columns of numbers are data taken from the safety evaluation of a prototype advanced traveler's information system called ADVANCE (Dingus, 1997). In that evaluation, a set of event categories were identified that included injury accidents, non-injury accidents, near misses, driver errors when a hazard was present and driver errors when a hazard was not present. I have treated the various events as Poisson variables in the remaining columns of Table 1. It is acknowledged that some researchers question the appropriateness of this model for crash data (Glauz, Bauer, and Miglet, 1985).

Certain features of this analysis are of special interest. First, the ADVANCE accident or crash data were taken from archival records for the preceding year. This is important because the crash occurrences are being obtained from a period where the ADVANCE system could not have possibly influenced the occurrence of crashes because it was not yet deployed. It is also important to note that the exposure associated with the crash statistics is 75.5 million vehicle miles traveled as opposed to the 487 miles observed during the ADVANCE baseline study itself. This enormous difference in exposure has implications for the reliability of the point estimates themselves. As indicated in the last column, the 95% confidence interval for near-misses includes zero, for example. The importance of this will become clear shortly.

Figure 1 shows an example of a safety pyramid (sometimes called Heinrich's Triangle) applied to the ADVANCE Baseline study. The triangle depicts the increasing frequency of occurrence of different measures of safety. The logic of the hazard analysis is that if one can take measures from the lower (more frequently occurring) strata of the triangle, it should be possible to predict the rate of occurrence for higher (rarer) strata. It is here that the implications of a zero near- miss rate become clearer. Recall that the number of crashes expected with a device for a given time period equals the number of incidents observed with that device during a time period times and the crash-to-incident ratio for that device. It is clear that such a ratio is undefined with a denominator of zero when the incident is defined as a near miss in this example.

Driver errors (e.g., as evidenced by lane exceedences, speed variation, above-normal braking due to a delayed object or event detection) are more numerous and might still fit the logic of the hazard technique. Some researchers have attempted to classify such errors as "intended" versus "unintended." Driver intent is divined by reference to observable criteria such as whether or not an object (e.g., another vehicle) was in proximity to the host vehicle at the time. It appears that the appeal of this approach is to credit the driver with the wisdom to know when it is acceptable to relax his or her lane keeping, speed maintenance, and the like. My view is that accurately inferring the driver's intent from a small set of observables is a difficult task. There is also the fact that many crashes appear to occur when drivers least expected them (e.g. Wiacek and Najm, 1999). This causes me to think that while the conditional probability of a crash given an unintended driver error is greater than the conditional probability of a crash given an intended driver error, the latter is not equal to zero. Thus, it appears that if one wishes to develop the hazard analysis method further, it would be prudent to measure driver errors regardless of the presence or absence of a hazard in order to obtain more counts, greater statistical stability and acknowledges the possibility of faulty driver judgement or complacency.

This philosophy presumes that driver errors are also related to crash occurrence. A lane exceedence can logically be considered the critical event that preceded a lane change crash or a roadway departure crash, a head-on crash (for undivided roadways). It can be shown statistically that speed variance is correlated with crash occurrence (Garber and Gadiraju, 1989). It can be demonstrated that close car following greatly increases the risk of a rear-end crash if the lead vehicle brakes suddenly and that such aggressive driving is correlated to traffic violations (Evans and Wasielewski, 1982). An initial link between visual demand associated with in-vehicle devices and crash incidence has been forged based on analysis of crash records (Wierwille and Tijerina, 1995).

Despite the intuitive appeal of the method, it is not without critics and it is in need of further refinement. Problems with Traffic Conflicts Technique (TCT)-based approaches have included controversy over the most basic of elements, the definition of a conflict or "near miss." Indeed, variation in definitions for "near miss" makes it virtually impossible to compare and contrast studies or combine studies in meaningful ways to assess the validity of the TCT.

Williams (1981) has shown that property damage crashes are poor predictors of fatal crashes. This may be because driver behavior will differ depending on which of the accident types the driver is attempting to avoid. Williams (1981) modeled different crash types: fatalities, injury crashes, property damage crashes, minor altercations (not police-reported), traffic conflicts from severe to trivial slowdowns. He demonstrated that the distribution of accident

Table 1. ADVANCE Hazard Analysis Example.

	ADVANCE Baseline Analysis				
	Counts[a]	Exposure, mvmt, t[b]	rate/mvmt[c]	var(rate)[d]	95% CI[e] for rate/mvmt
Injury Accident	164	75.5	2.17	0.0287	[1.83, 2.50]
Non-injury Accident	387	75.5	5.12	0.0678	[4.61, 5.63]
Near Miss	3	0.000487	6160	12 648 871	[-810, 13 131]
Driver Error, Hazard Present	54	0.000487	110882	2.2768×10^8	[81 307, 303 071]
Driver Error, No Hazard Present	?	?	?	?	?

Notes: a. Counts modeled as Poisson variable.

b. Exposure represents Poisson exposure parameter, t estimate

c. rate/mvmt represents Poisson occurance rate parameter, λ estimate = counts/exposure .

d. Variance of λ estimate is VAR(λ est) = λest./t.

e. 95% CI for λ is approximately λ est $\pm$ $z_{0.975}\mathrm{VAR}(\lambda)^{1/2}$

types (e.g., right angle, acute angle, rear-end, head-on, run off road, stationary object), time of day, and accident location are significantly different between damage only and injury accidents. Thus, it may be inappropriate to even compare neighbors along the severity continuum much less from

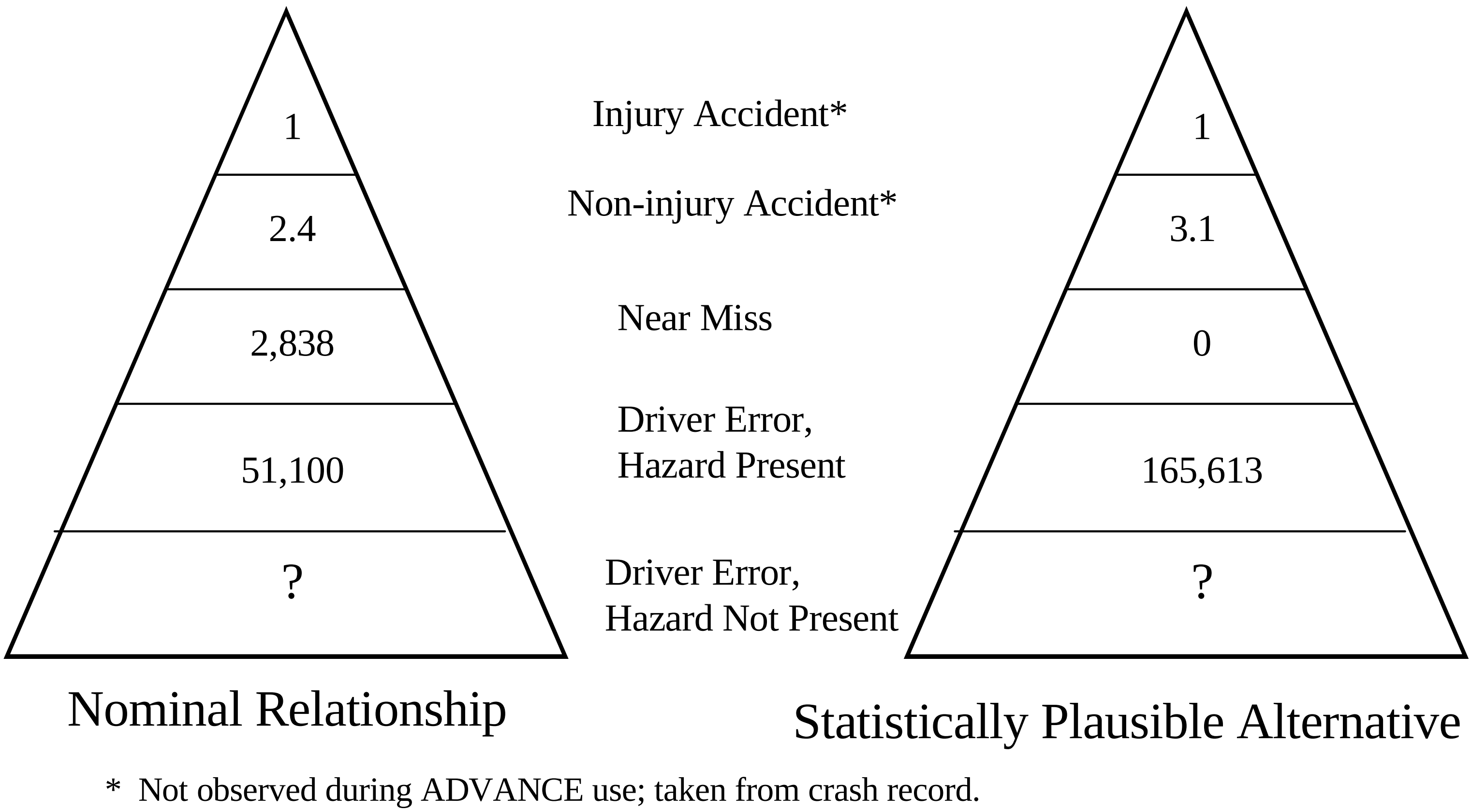

Figure 1. Heinrich's Triangle for ADVANCE Baseline Study.

the bottom to the top. It appears that severe accidents should not be directly estimated from minor traffic conflicts.

Drawing predictions from Heinrich's Triangle is similar to building predictions from correlated data. Assume one wishes to predict variable C from knowledge of variable A and one has the correlation between A and a variable B and the correlation between B and C. On the face of it, it seems reasonable think that such correlations would be sufficient to accomplish the predictive task. However, Tijerina et al. (1996) demonstrated that even if the correlations between A and B and B and C are as high as 0.7 (and this is unusual in human factors studies, the correlation between A and C can range from perfect (1.0) to no correlation (0.0), i.e., the relationship is completely indeterminate. Thus, caution is urged in making such extrapolations.

Defining conflicts or 'near misses' in terms of evasive maneuvers is illogical in light of the fact that in a large percentage of crashes (e.g., 80% for some rear-end and lane change crash scenarios), there is no precrash evasive maneuver (Wiacek and Najm, 1999). Defining a conflict in terms of an event (i.e., occurrence of an evasive maneuver) is also not as appealing as defining a conflict in terms of a situation. Recent attempts to get around this problem focus on the proximity and relative motions of two or more involved vehicles using metrics such as time- to-collision or TTC (Campbell, Joksch, and Green, 1996). Of course, concern remains that defining TTC values closer and closer to zero increases the predictive power of the measure but it may be at the cost of TTC values almost as rare as collisions themselves. Now situations where there was no evasive action could still be identified as conflicts. However, care must be taken that the operational definitions are not simply "old wine in new bottles," i.e., that time-to-collision is so highly correlated with evasive maneuvers as to make them synonymous. There is the pervasive concern that the more severe the conflict (e.g., the shorter the TTC), the rarer the conflict events. At some point, a crash is a *fiat accompli*, meaning the correlation between the conflict and a subsequent crash is almost 1.0. It is also about as hard to observe, and so is virtually useless for prediction.

Developing the Distraction-Safety Link: An Object Lesson from the Smoking and Cancer Debate

There can be a need to establish a link between distraction and driving safety from which an important lesson might come from the smoking debate. The most persuasive evidence that linked smoking as a cause of cancer (though still debated by the tobacco lobbyists) was NOT simply finding that smokers had higher rates of cancer than non-smokers (akin to finding that drivers with cell phones had higher rates of crashes than drivers without cell phones; akin to finding that drivers had fewer crashes with than without a Collision Avoidance System (CAS)). Rather, the most compelling evidence was discovering a systematic trend toward higher cancer rates with increased smoking rates.

It is important to beware the correlational interpretation about what is the cause and what is the effect. For example, an empirical finding indicates that children with pets are better behaved than children without pets (Abelson, 1995). The causal attribution might be that the responsibility of caring for a pet matures the child. However, an equally plausible interpretation of the same empirical result is that ill-mannered children are not allowed to have pets! To translate to, say Collision Avoidance Systems technology evaluations, consider the following. Empirical results determine that drivers (cf., children) with collision avoidance systems (cf., pets) have lower crash incidence (cf., are better behaved) than drivers without collision avoidance systems. The causal attribution might be that the CAS technology (cf. Pet) enhances safety (cf., matures the child). An alternative but equally plausible explanation is that reckless drivers (cf., ill-mannered children) do not use CAS technology in their cars (cf., are not allowed to have pets).

One major implication of this example is that comparing groups with and without a safety-relevant intervention can be very tricky. Furthermore, normal Human Use Review Panel (HURP) screening procedures generally identify candidate volunteers with good driving records, proof of insurance, etc. (cf., well-behaved children). If the volunteers get the safety-relevant intervention and are compared to a non-selected at-large population (cf., ill-mannered children, possibly), this may heighten the probability of a spurious interpretation. This is one major flaw in the Traffic Conflicts Methodology to predict crash incidence as applied to ITS. Crash occurrence is, in field operational tests, virtually always estimated from conditions where the safety-relevant intervention which could not have had an effect and for whom the population of drivers may be fundamentally different than those in the formal study.

Consider once again the question: “Does smoking cause cancer?” Simply showing that people who smoke contract lung cancer more often than people who don’t smoke is not persuasive. The Tobacco Institute and cigarette manufacturers have rallied numerous counter-explanations. Smokers are more anxious than non-smokers and it is tension that causes cancer. Smokers drink more coffee than non-smokers and it is coffee that causes cancer. More men smoke than women and it is just that men happen to be more susceptible to cancer than women. And on and on and on. Even though each of these counter-explanations could be rebutted by appropriately collected data, there was always the possibility of a new explanatory variable, preferably one for which no good data exist (e.g., it is the level of psychological tension that is highly correlated with cancer risk).

As Abelson (1995) points out, a much stronger approach is to spell out the details of the proposed causal mechanism implicating smoking and then test the consequences that this mechanism would imply. This was in fact done in the cancer research community, and to good effect. Consider this approach, again by direct analogy between smoking and driver distraction.

In simple terms, the postulated causal mechanism for cancer (cf., crashes) is that tobacco smoke (cf., in-vehicle devices) contains substances that are toxic to human tissue when deposited by contact (cf., if the drivers eyes, mind, and sometimes hands away from driving). The more contact (cf., the more demanding the device or more frequent the use of that device while driving) and the greater the toxicity (cf., the greater the distraction), the higher the likelihood of contracting cancer (cf., the greater the crash hazard exposure). Some empirical implications of such a mechanism are provided below:

1. The longer a person has smoked cigarettes (cf., the more demanding or more greatly used a device) , the greater the risk of cancer (cf., if the greater the risk of crash involvement).

2. The more cigarettes a person smokes over a given period of time, the greater the risk of cancer (cf., the greater the use of a device, the greater the likelihood of crash involvement);

3. People who stop smoking have lower cancer rates than those who do not stop smoking (cf., drivers who stop using the cellular telephone while driving have lower rates of crash involvement than those who do not stop using the cellular telephone while driving);

4. Smokers' cancers tend to occur in the lungs and to be of a particular type (cf., distraction-related cases tend to be rear-end, lane change, and intersection crashes with contributing factors like 'did not look', 'looked but did not see', 'saw but misperceived');

5. Smokers have elevated rates of other respiratory diseases [cf., distracted drivers have elevated rates of near-misses (i.e., traffic conflict with another vehicle present) and driver errors (e.g., running a stop sign or traffic light, turning onto the wrong street, veering out of lane, etc.)]

6. People who smoke cigars, or pipes, the smoke usually not being inhaled, have abnormally high rates of lip cancer (cf., , 'looked but did not see' cases increase with voice-based systems).

7. Smokers of filter-tipped cigarettes have somewhat lower cancer rates than do other cigarette smokers (cf., drivers with hands-free cellular phones have a somewhat lower crash involvement rate than hand-held cellular phone users);

8. Nonsmokers who live with smokers have elevated cancer rates, a result of passive exposure to smoke (cf., crash-related injury among passengers is higher among drivers who use the cellular phone whilst driving as opposed to drivers who do not use the cellular phone whilst driving).

As pointed out by Abelson (1995), all of these implications have moderate to strong empirical correlational support and the case is persuasive because it is so coherent. No additional explanatory mechanism seems required since no anomalous results remain to be explained. For instance, if smokers were found to have four times the rate of fallen arches, this would introduce a nagging bit of incoherence that begs explanation. Further, if another factor like an anxious personality were the true cause of cancer, it would be very difficult to explain results 3,4,5,6, and 7.

Conclusions

It is clear that safety evaluation of driver distraction associated with in-vehicle information and telecommunications systems is a complex undertaking. The prediction of safety benefits or costs is difficult at best. Hazard analysis methods, despite their limitations, play an important role for early-on evaluations as opposed to retrospective evaluations. It is my belief that the prospects to predicting the number of crashes that might arise with the use of a particular ITS technology are poor. Elimination of improper driver behavior (i.e., driver errors) or operational problems may be the more useful goal of a safety evaluation effort. Beyond this, I recommend that safety evaluations be incorporated as a part of iterative testing throughout the life cycle of a product with the goal of continuous product improvement. This recommendation is in keeping with the best practices in the industry and the expectations of the driving public.

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