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From theory to practice in road safety policy: Understanding risk versus mobility

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ABSTRACT

This paper reviews theoretical issues surrounding transport safety modeling and the implications for road safety policy. The behavioral mechanisms that affect transport safety are typically not considered in safety modeling. These issues are discussed in the context of trade-offs between risk-taking, as perceived by travelers, and other mobility objectives and the attributes associated with them. This is an extension of other theoretical frameworks, such as risk compensation, and attempts to integrate some of the previous frameworks developed over the years. Various examples of behavioral adaptation to specific policies are discussed and linked to the framework. These issues are then discussed in the context of improvements to empirical work in this area and the linkage of theoretical frameworks to crash modeling, in particular the estimation and use of Crash Modification Factors. Conclusions suggest that there are many deficiencies in practice, from estimation of models to choice of effective policies. Progress is being made on the former, while the publication of practical guidance seems to have substantial lags in knowledge.

1. Introduction

The primary objective of road safety policy is to make travel safer. Over the last 40 years major effort has been devoted to achieving reductions in vehicle crashes and their severity in all developed countries, with mixed results. For example, Sweden and the United Kingdom, have seen dramatic reductions in both fatal and injury outcomes over the last 40 years, whether measured per capita or per vehicle-kilometer traveled (VKT), both having the best overall safety records of any country. The US, on the other hand, has seen smaller reductions. For many years the total number of fatalities stagnated at about 42,000 per year, only recently dropping in 2008 with the global financial crisis.[1]

Road safety policy is typically the domain of many different disciplines. This includes traffic engineers, economists, psychologists, statisticians, public health professionals, and more recently urban planners. Frequently these different disciplines approach road safety policy from different perspectives. Placement of road safety policy within the broader framework of transport behavior, choice, and economic decision making tends to be lacking. For example, the choice of mode can have a major impact on overall levels of safety and understanding how relative modal risk affects these decisions is often not considered, even for non-motorized modes.[2] Transport policy that affects the choice of mode may have implications for overall road safety.

A good example of this is how increases in the use of non-motorized modes can affect overall safety. Jacobsen (2003), in a widely cited paper, suggests that there is 'safety in numbers' providing a protective effect for bicyclists and pedestrians. Theoretically this might occur due to the presence of non-motorized modes leading to reductions in speed; that is motorists take greater care when they interact with more non-motorized modes. The increase in the visibility of non-motorized modes may also lead to greater awareness and more careful driving. Alternatively, the analysis in Jacobsen could be spurious; that is, there is another underlying mechanism (such as improved bicycle and pedestrian infrastructure) that both attracts more non-motorized activity and also makes it safer. Thus, a fuller understanding of behavioral responses can lead to better policy decisions.

Another important issue for a better understanding of how to improve road safety is how the results of research studies are

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[1] See http://www-fars.nhtsa.dot.gov/Main/index.aspx for total fatalities and other aggregate data for the US.

[2] Noland and Kunreuther (1995) examined how perceptions of risk affect the use of bicycles as a commute mode.

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applied in practice. As many of the debates over policy are politically controversial the actual implementation of policies and interpretation of research results is not simply achieved. Examples include the repeal of motorcycle helmet laws in the US, which are proven to be effective at reducing fatalities, and debates over speed cameras in the UK (Delaney, Ward, Cameron, & Williams, 2005), also shown to reduce fatalities (Gains, Nordstrom, Heydecker, & Shrewsbury, 2005). Speed limit policies in particular have proven difficult to implement for safety; the US repealed a nationwide 55 mph speed limit that accounted for large reductions in traffic fatalities when initially implemented in the mid-1970s with subsequent increases in fatalities and crashes on repeal (Friedman, Hedeker, & Richter, 2009). Much of the debate over speed control now centers on urban areas where efforts to implement traffic-calming features are often met with controversy by vocal minorities (Taylor & Tight, 1997).

The measurement of traffic safety and how this influences policies is also dependent on the choice of metric. The scale of measurement, whether by mode, road type, or area can influence policy. For example a focus on only motorized modes may ignore the consequences for pedestrians. The actual metric chosen to measure casualties may also have an impact on policy choice (Johnston, 2010). These may include total deaths and injuries or be measured based on total travel (per VKT) or per capita. Per capita measures allow one to compare road casualties with other public health problems. VKT based measures presume that casualties are an unfortunate consequence of mobility, which is seen as beneficial. This leads to perverse effects, such as in the US, increased mobility (measured by VKT) will tend to lower the rate of casualties per VKT, suggesting to policy makers that there is progress in reducing casualties, even when totals are increasing. Defined targets for total casualties, and especially fatalities, can lead to changing "…the institutional mindset from one of managing a by-product to one of viewing safety as a fundamental outcome…" (Johnston, 2010, p. 1177).

This paper examines several of the issues surrounding road safety policy from a behavioral perspective, explicitly considering how safety policy influences mobility. This begins with a discussion of theoretical frameworks for understanding road safety behavior and the formulation of a proposed theoretical framework that unifies many of the previous theories. Various examples of behavioral adaptation are discussed. This is followed by a discussion of modeling and data issues associated with empirical estimations. Interpretation and use of model results is then discussed. Conclusions examine how to improve the process of analyzing road safety policies with the hope that improvements in knowledge and actual reductions in crash and severity outcomes can be achieved.

2. A review of theoretical frameworks

Road safety policy has generally been pursued using the tools of enforcement, education, and engineering. Enforcement is assumed to lead to reduced risk taking among motorists, education provides a means of improving driving skills and increasing awareness of potential risks, while engineering is aimed at improving both the crash integrity of the vehicle, survivability of crashes, and changes to the road infrastructure to reduce crashes and their severity (i.e., making the road itself more "forgiving"). The theoretical constructs surrounding the formulation of policy in these areas, especially in the engineering realm, has generally assumed a deterministic and fixed response to any intervention that is estimated to reduce crashes. In essence, this assumes that individuals do not change their behavior in response to an engineering improvement or policy.

Devising a theoretical framework for how effective various policies are requires the inclusion of a behavioral element into the theory, and this could substantively modify conclusions about the effectiveness of various interventions. The effect of behavioral responses has long been a controversial topic and was originally noted in the seminal work of Smeed (1949), who stated:

> "It is frequently argued that it is a waste of energy to take many of these steps to reduce accidents. There is a body of opinion that holds that the provision of better roads, for example, or the increase in sight lines merely enables the motorist to drive faster, and the result is the same number of accidents as previously. I think there will nearly always be a tendency of this sort, but I see no reason why this regressive tendency should always result in exactly the same number of accidents as would have occurred in the absence of active measures for accident reduction." (Smeed, 1949, p. 13)

Smeed thus recognized the issue as early as 1949, and recognized that any response would not fully off-set the increased risk from faster driving. Probably the first formal analysis of this idea dates to Taylor (1964) who studied the galvanic skin response[3] of test drivers and determined that there was a measurable change when drivers encountered riskier situations. Taylor posited that driving behavior is regulated in such a manner as to control risk by maintaining a given level of anxiety, and this can be controlled by speed choice. He also suggested that "Driver behaviour could be more directly manipulated by deliberate introduction of 'artificial hazards'…" (Taylor, 1964, p. 450).[4]

2.1. Cognitive models

Following the work of Taylor (1964), the first psychological theory was originally proposed by Näätänen and Summala (1974). This was the "Zero-Risk theory" and the implication for road safety is discussed in Summala (1988). The main hypothesis proposed is that drivers adjust to road risks and therefore do not subjectively experience it under normal driving conditions. This theory recognizes an implicit trade-off of risk with mobility, although this is expressed as the driver's motivation. That motivation can include other objectives, such as conservation of effort, or the excitement of speed. The rarity of drivers actually experiencing risk thus motivates them to increase their speed to satisfy other motivations for driving. Summala (1988) states that "the key to effective safety countermeasures is…to prevent [drivers] from satisfying their motives" (p. 500) and this implies some form of speed control.

Wilde (1982) formulated the risk homeostasis theory to explain risks in road safety. Wilde's research developed from psychological theories of human behavior and posited that individuals seek stimulus from achieving a specified target level of risk in their lives. Thus, any reduction in transport risk might increase risk-taking behavior to achieve the same target level of risk. Expanding this beyond just transport behavioral reactions, Wilde suggested that other risky behaviors for which individuals derive pleasure might also increase (e.g. rock climbing, sky diving, or other thrill-seeking activities). The homeostatic mechanism described by Wilde was that target risk would remain constant and that effective policies must be aimed at reducing the desired target risk. One assumption behind this theory is that individuals can accurately perceive their

[3] Galvanic skin response is a measure of how the skin conducts electricity and varies with the moisture content of the skin. In short, when one sweats it is a measure of psychological and physiological arousal (e.g. increased heart rate and alertness).

[4] This is of course, what is accomplished by some traffic calming techniques.

target levels of risk, which can clearly be disputed. The risk homeostasis hypothesis led to controversy and attempts at empirical verification; results over the years have been mixed, but with a general consensus that there is some behavioral adaptation, but not a complete off-set as the theory implied (O'Neill & Williams, 1998).

Michon (1985) provides a review of driver behavior models and a critique of behavioral adaptation theories. Michon's focus is on developing a "control theory" approach based on understanding the underlying cognitive mechanisms of individuals. This would allow for the development of a computational framework to predict the implications of different safety policies. Michon's view is that risk homeostasis and compensatory models do not explain which stimuli affect perceptions of risk, and that they have no individual-based theory. Michon's rule based approach, however, is too complex to implement and could be subject to error if any cognitive or behavioral input is incorrect. He uses a simple example of a pedestrian crossing at a traffic light, but the rules imposed are all based on the pedestrian obeying various traffic rules and not reacting to the context of the situation (for example, situations such as crossing against a red signal if there is no traffic in sight would not be risky).

Michon (1985) cites the work of Klebelsberg (1971, 1977, published in German) as developing a control process based on balancing subjective and objective risk. This work examined the equivalence of subjective (perceived) and objective risk and made the argument that when objective risk exceeds perceptions of risk, then there may be a safety problem. Alternately, when perceptions exceed the objective risk level there is then a safety margin that is too large (i.e., while not stated, this assumes an economic argument that there is an optimal level of safety). Klebelsberg is essentially proposing a risk threshold model similar to Näätänen and Summala (1974); that is safety problems do not arise until a given perception of risk exceeds the objective level of risk. Using a driving simulator, studies have been used to empirically investigate these issues, and have found some empirical support (Lewis-Evans, de Waard, & Brookhuis, 2011).

Michon (1989) provides additional discussion of the distinction between "aggregate models" of road user behavior and "process models" of individual driver behavior. This provides a useful dichotomy between economically-based models that describe aggregate behavior and psychology-based models of individual driver behavior. It is stated that the former assume rational behavior, while the latter can explain mental processes and actual behavior. This really gets at the crux of the difference between psychological versus economic approaches to studying road traffic safety. One benefit of economic or aggregate approaches is that they are more practical and easier to develop hypothesis tests for that are policy relevant; alternatively, psychological approaches have been tested using simulator studies which will suffer from caveats as to how realistic they are for modeling real behavior.

A very detailed review of many theoretical models in road safety was conducted by Ranney (1994). He discusses the distinction between aggregate versus individual models (similar to Michon, 1989). Risk compensation models are aggregate models, or can be described as "functional models of driver behavior", that include driver motivations. While not explicitly stated by Ranney (1994), this implies trade-offs between risk and other motives. The criticism of these models is that they provide no detail on individual behavioral mechanisms (again, similar to Michon's (1989) criticism of risk homeostasis). Another concept discussed by Ranney (1994) is that of "automaticity", in which certain driving functions are processed without much, if any, cognitive effort. When unexpected events occur, then knowledge-based processing is required by the driver, implying the need for detailed cognitive models. Motives may also vary based on situations — of course, this is another way of thinking about trade-offs; and the assumption is that compensation can occur at different levels (or hierarchies) of "control", from automaticity to the need for inherent knowledge of driving tasks.

Fuller (2000, 2005) and Fuller and Santos (2002) proposed a broader perspective on homeostasis theory. They proposed that drivers seek to maintain a given level of task difficulty, which was termed task difficulty homeostasis. For example, if a driver approaches a complex junction she will reduce her speed as navigating through the junction has a higher level of task difficulty. Speed is proposed to be the primary mechanism whereby drivers regulate the difficulty of the task. However, speed choice also is recognized to be determined by other motivations, such as time constraints. A key component of this theory is that different drivers have different capabilities and maintain a buffer between the difficulty of expected tasks and their individual capabilities to safely complete the task. Capability levels may vary with conditions and certainly vary with individuals (i.e., by age, experience, and factors such as intoxication or fatigue).[5] One of the key features of Fuller's model is the proposition that individuals do not correctly perceive statistical risk and cannot use this information in their decisions (Rothengatter, 2002). From an empirical perspective Fuller also suggests that it is quite difficult to measure perceived risk, and sees this as a problem with empirical testing of Wilde's theory.

Fuller (2008) extends his task difficulty homeostasis theory to what is now known as "risk allostasis" theory.[6] This is defined as "maintaining a particular level of task difficulty or risk feeling that *varies* according to an individual's needs and circumstances". Empirical work by Fuller, McHugh, and Pender (2008) and Kinnear, Stradling, and McVey (2008) suggests that there is an increasing and linear relationship between speed and task difficulty and feelings of risk. Slovic, Finucane, Peters, and MacGregor (2004) proposed an "affect heuristic" associated with experiential feelings of risk, which also leads to automaticity based on these feelings as suggested by Ranney (1994).

Using a simulator study, Lewis-Evans and Rothengatter (2009) cannot replicate the finding of a linear relationship between speed, task difficulty and feelings of risk, but instead find a threshold effect; that is, task difficulty and feelings of risk only increase after a given level of perceived risk (measured by speed for different road types) is surpassed. This is consistent with Näätänen and Summala's (1974) zero-risk threshold model. Lewis-Evans and Rothengatter (2009) also point out that Fuller's risk allostasis model suffers from the same critique of risk homeostasis theory that assumes individual drivers are constantly monitoring their target level of risk; in this case they are constantly monitoring the difficulty of the task and their feelings of risk.

Lewis-Evans and Rothengatter's (2009) critique of Fuller's model suggests that there is still a lack of consensus on safety theories that rely on cognitive processes. In fact, after many years of analysis it seems that the zero-risk threshold model is a reasonable simplification of the underlying cognitive process, whether defined based on risk, feelings of risk, or task difficulty. From this perspective, economic models might provide a more useful approach for understanding aggregate behavior. A useful summary of the distinction between cognitive and economic approaches is

[5] Fuller's theory has parallels to theories of air traffic safety management. In managing air traffic, safety levels are partially mediated by the capabilities and task difficulties that air traffic controllers face (Majumdar, Ochieng, & Nalder, 2004).

[6] Allostasis is defined as: "the process by which the body responds to stressors in order to regain homeostasis." (http://oxforddictionaries.com/definition/english/allostasis).

provided by Hedlund (2000). Verification of cognitive driving theories is commonly being done using driving simulators, an approach that Hedlund (2000) critiques as the respondents are in an artificial situation where they are not at risk, compared to actual drivers. Given the multitude of individual responses to safety policies, Hedlund argues that aggregate data is needed to examine risk compensation or behavioral adaptation; basically one must evaluate system-wide effects rather than individual behavior.

2.2. Economic models

Within the economics literature, the first analysis of these issues was by Peltzman (1975), which has become known as "risk compensation" theory. Risk compensation proposes that any regulatory measure to reduce risk will lead to an off-setting response by the driver that reduces the predicted engineering reduction in risk or even negates it. Peltzman's focus was on regulatory measures to improve vehicle safety that were implemented in the mid-1960s (in the US). He challenged the effectiveness of these policies by estimating models that showed a complete off-set to the expected risk reduction. Much of the increase in risk was estimated to come from increased pedestrian risk due to an increase in "driving intensity". That is, Peltzman depicted a picture of increased driver recklessness due to the reduced risk to drivers from driving safer vehicles. This was presumed to both increase the crash rate (although survivability might be improved), but in particular to lead to more pedestrian fatalities. Of course, an inconsistency in his argument is that we would also expect pedestrians to react to the increased risk of more reckless drivers by being more careful (i.e., changing their behavior). Peltzman was seeking to discount the benefit of vehicle regulations aimed at saving lives.[7]

Peltzman's analysis set off a firestorm of dissent among road safety researchers (see for example, Graham & Garber, 1984; Robertson, 1977, 1981). However, despite this, the basic framework of behavioral adaptation or risk compensation is generally accepted, though perhaps not the complete off-set proposed by Peltzman (and later by Wilde, 1982). For example, it is self-evident that drivers take greater care when risk increases during rainy or snowy weather conditions, by reducing their average speeds. Other research has largely confirmed that some element of risk compensation likely occurs (for example, see Conybeare, 1980; McCarthy, 1986; Singh & Thayer, 1992; Traynor, 1993; Zlatoper, 1984).

One unfortunate result of Peltzman's original study was the phrasing used to describe risk compensating behavior: "More speed, thrills, etc., can be obtained only by forgoing some safety" (p. 681) and a driver who reacts as being a "belted-milquetoast-turned-daredevil" (p. 682). The actual mechanism in which risk compensating behavior takes place likely involves more subtleties than just increased speed and recklessness; for example changes in driver's motivation as expressed by Näätänen and Summala (1974). As examples, other possibilities include a greater propensity to let teenagers drive unsupervised, since the vehicle is safer. It could also involve a shift away from other safer modes of travel, such as public transport. In particular it may result in more travel overall. One example is that improved safety in air transport since the 1950's has undoubtedly led to increased air travel. If current air safety rates were similar to the 1950's there would be about one major crash worldwide every week, which would undoubtedly have some effect on overall demand.

This leads to another element of risk compensating behavior that is often overlooked. How individuals perceive risk reductions (or increases) may not be accurate. It is well known that large transport accidents, such as air accidents or major rail accidents tend to receive far more press coverage than day-to-day road accidents. Individuals and society tend to view the risks of various activities differently, with those occurring less frequently, but with large consequences being considered more risky, even when they are not. This clearly has an effect on how individuals perceive the relative risks of accidents (Slovic, Fischhoff, & Liechtenstein, 1982) and can influence the choices individuals make. These perceptions may also be experiential and non-analytical, i.e., drivers do not explicitly weigh the costs and benefits of specific measures or actions (Slovic et al., 2004). Drivers may be unaware of many safety features of modern vehicle design and thus would not perceive that the vehicle is inherently safer (although auto manufacturers may advertise these features). One would expect drivers to only respond to those safety features that affect the driving experience, such as better braking systems (anti-lock brakes) or better vehicle performance (such as tires with better friction).[8] The visibility of safety belts and airbags may also affect driver behavior.

Subsequent to Peltzman (1975), the first utility based framework for thinking about risk compensation can be attributed to O'Neill (1977). O'Neill develops a utility maximization equation that is based on speed choice to regulate risk and shows how the relationship between speed and risk (i.e., the functional form of the equation) can affect whether risk compensation occurs and by how much, such as no offset, partial or full offset, or even resulting in an increase in total risk. Janssen and Tenkink (1988) also formulate a model based on utility maximization where individuals trade off risk versus travel time. Their focus is on showing that risk homeostasis behavior could occur.

Blomquist (1986) likewise proposed an economic model that involves maximization of the utility of traffic safety behavior, based on driver's having good information for making rational decisions. His model balances the costs of increased safety with other driver goals that may be unrelated to safety. In particular, he posits that within travel time constraints drivers make optimal utility maximizing trade-offs, and he cites various studies of variation in safety-belt usage in support of his model. Any exogenous improvement in road safety, would therefore induce a reduction in the safety-taking effort of drivers, in other words risk compensation.

In considering utility maximization as a formulation of the choice of risk, an issue is what motivates the driver? Rothengatter (1988) argues that it is not just risk (or its avoidance) that motivates how drivers select their speed, but that there may be other motivating factors.[9] This identifies the shortcomings of these utility frameworks. Transportation demand is a derived demand motivated by the desire to access various activities; and while there is a motivation to reduce travel time, other attributes are typically considered in the choice of how to access activities. Rothengatter (2002) also considers the impact of environmental factors on attitudes to risk taking; in a utility framework one can consider how attitudes might influence the objective or motivation for a trip.

Hedlund (2000) provides some useful rules for thinking about how risk compensation and behavioral adaptation may affect the outcome of safety policies. His first rule states that compensation is not likely to occur if the safety improvement is not visible or obvious to the driver. Many vehicle safety regulations may result in

[7] Peltzman was at the University of Chicago, well known for it's free market anti-regulatory perspective on economic policy.

[8] Hedlund (2000) emphasizes that only those safety measures that are visible will result in risk compensation.

[9] Rothengatter (1988) suggests that the pleasure of driving fast may be one motivation.

vehicle improvements that do not affect vehicle performance and thus are not visible to the driver. The second rule focuses on how the policy change may affect the individual driver. This includes how the policy may affect task performance, how it may affect attitudes, but most critically how it affects perceptions of risk and whether these are in line with objective risk. The third rule focuses on motivation or the maximization of utility; that is the trade-offs that drivers make in fulfilling their objective. If there is no motivation to change behavior (or no trade-offs made) then risk compensation will not occur, but this seems unlikely. The last rule is less relevant to the driving task, but concerns how much control the individual has. In driving, there is considerable autonomy to compensate; this may be less true in other safety situations.

3. A proposed theoretical framework

As discussed above, the original road compensation hypothesis attributed to Peltzman focused on an increase in "driving intensity". A more reasonable approach is to consider the off-setting reductions in risk to be a result of increases in mobility. This fits within the framework originally proposed by O'Neill (1977) of utility maximization, in that drivers make trade-offs between time and safety.

The proposed theoretical framework extends the utility maximization framework to a generalized cost approach. One criticism of these models, discussed above, is the inability of drivers to measure and perceive risk. This is certainly an important issue in understanding the cognitive process which underlies any behavioral adaptation and is the foundation of many models in psychology and economics. The primary concern of any safety analysis is to understand how policy affects safety and while understanding individual behavior and its shortcomings is useful, it is the aggregate response of any policy that is most useful from a societal perspective. There is no need in this sort of framework to measure or analyze the details of how individual drivers may balance trade-offs from "moment to moment", which is probably unrealistic in any case (Michon, 1989; Summala, 1988). Thus a formalized theoretical framework that considers multiple trade-offs and provides guidance to analysts on how to structure the analysis of aggregate data is the main intent here.[10]

Dulisse (1997) provides a useful graphical depiction of this relationship. We elaborate on this by focusing on how safety and mobility are traded off. This is graphically depicted in Fig. 1 which displays concave isoquants of equal levels of safety and mobility with a convex preference curve. Any exogenous technological change can have an impact on both mobility and safety and is represented by the higher isoquants. A technological change could include any number of things such as safer vehicle design, changes in road infrastructure such as more controlled-access facilities, or changes in speed that increase mobility.

If the initial levels of mobility and safety are set at point A on the graph, the new levels after a new technology or policy is introduced will be dependent on the relative shape of the preference curves. Point B represents the engineering hypothesis where all the benefits are associated with reductions in risk (more safety) with no off-setting behavioral reaction. Point D shows a case where risk might even increase due to large increases in mobility. Point C is the most likely outcome where some of the benefit of the new technology reduces risk while some increases mobility; this is the

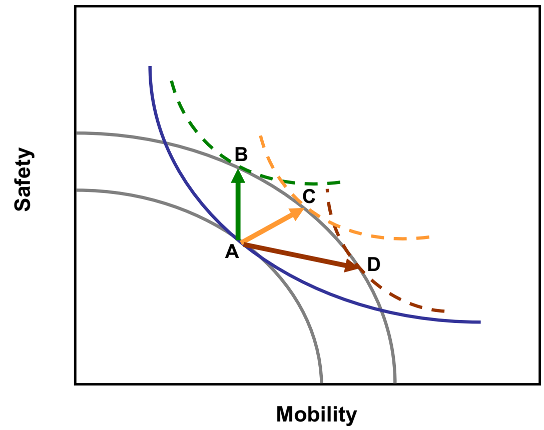

Fig. 1. Trade-offs between safety and mobility.

classic case of an off-set to any reduced risk and implies that off-sets can occur without increased driver recklessness.

Transport economics views travel demand (or mobility) as a function primarily of travel time and the price of travel, with the purpose of travel being to access various activities. Most of the costs of a trip are associated with the relative value of time as perceived by individuals. Choices are typically made between different modes of travel (mainly driving versus public transport) on the basis of the relative difference in monetary cost and travel time. Other factors can be important such as reliability and comfort of the mode, as well as the relative safety of alternative modes.

For those choosing to drive a car, the choice of speed provides an explicit trade-off between time and risk, assuming that drivers accurately perceive either of these factors. Elvik (2010) argues that driver choice of speed is not objectively rationale. This is largely based on the misperceptions drivers have about the relative risk of higher speeds and their misperception of the travel time savings associated with higher speeds. This makes identification of the preference curves in Fig. 1 problematic; individuals, in general, cannot accurately perceive the relative risks and travel time associated with different trade-offs. Therefore actual choices will be based on perceptions that are likely inaccurate.

Drivers may also speed both unintentionally and intentionally. The former may be distracted by other road or traffic events and not observe posted speed limit signs while the latter may perceive that it is not dangerous to exceed the posted limit. Salmon, Young, Lenné, Williamson, and Tomesevic (2010) find this occurs in a study that included intensive measurement and recording of driver behavior followed by intensive interviews, albeit in a small non-representative sample.

Some recent studies examine the risk-mobility trade-off. Yannis, Kanellopoulou, Aggeloussi, and Tsamboulas (2005) conducted a stated preference analysis of the trade-offs between increased travel time (and cost) and reduced risk. They found significant effects demonstrating that drivers do consider this trade-off, although the results must be caveated given the shortcomings of stated preference surveys (Weiner, Puniello, Lau, & Noland, 2011). Rizzi and Ortúzar (2003) also conducted a stated preference survey by specifying different routes with different levels of risk and travel time and found again, that trade-offs are explicitly considered, with a value being put on safety.

Machin and Sankey (2008) examine how risk perceptions affect reported speeding behavior among 17–20 year old drivers. Measures of risk aversion were found to reduce the likelihood of reporting speeding behavior and this is off-set by personality indicators associated with more speeding. Research has also found

[10] Elvik (2006) proposes various "laws of accident causation", though admitting that these are really testable hypotheses and that the intent is to spur empirical research toward a more generalized theory of accident causation.

that drivers often over estimate their own driving capabilities and young drivers misperceive the potential risk of various driving situations (Deery, 1999; Svenson, 1981). Thus, age and experience of drivers are likely mitigating factors and it is, of course, well known that younger drivers have higher crash rates.

The capability of individuals to actually engage in mobility is also a critical determinant. This adds the additional element of how capable individuals are to engage in the tasks of driving as suggested by Fuller (2005). For example, mobility is clearly affected by individual characteristics, such as age, disability, or the overall ability to drive, as is their relative risk in different situations.

Mahalel and Szternfeld (1986) theorize that when driving tasks are made simpler, relative risk could increase. The mitigating factor is how the driver may perceive the reduction in task complexity. If drivers are over confident, then they may actually overcompensate for any increase in task simplicity, perhaps by not paying as much attention to road conditions. These types of cognitive issues are often overlooked but imply that a critical component of any model should include the perceptive ability of individuals. Fuller (2005) addresses these issues via his linkage of task to capability, but drivers need to be aware of what their capabilities are.

Driver distraction and fatigue may also play a role in the risk of driving. A relevant question is whether roads and vehicles perceived to be safer may influence the likelihood of drivers engaging in distracting behavior or not taking due care if they are fatigued. This is another form of compensating behavior. A relevant question is how drivers value the other tasks they are attending to? Cell-phone usage is one activity that clearly has benefits to drivers but that increases risk. What are the perceived benefits of other tasks that will distract the driver? If those tasks have high value they will be more likely to occur, but engagement in distractions will vary based on the difficulty of the driving task and the perceived risk of the road environment. Likewise the road environment may affect any subsequent recovery from driving errors that are made.

Considering these issues and building on prior theoretical models we can specify the utility of travel, *U*, as a function of price, *P*, travel time, *T*, capability, *C*, in-vehicle activities, A (such as those that lead to distractions), and risk, *R*.

$$U = f(P, T, C, A, R) \tag{1}$$

Consumers then seek to maximize their utility within the constraints of the given technologies available to them, as well as their own personal budget constraints. The specific functional form, *f*, will determine how a change in risk affects a change in other attributes, that is, the elasticity of substitution, which is an empirical question. Maximization of utility (or minimization of generalized cost) represents the motivation of the driver which is typically to increase mobility.

A key controlling factor is the trade-off with travel time, which is controlled by the choices of the individual. Speed choice has a clear link to risk. However, other individual choices that increase (or decrease) travel time may not simply reflect traveling faster. Various other unsafe behaviors may reduce travel time, such as running stop signs or lights, tailgating, and aggressive maneuvering. Even the choice of travel mode is largely determined by travel time choice and can affect personal safety (for example, choosing to drive versus taking public transport).

Other components of Equation (1) are also linked to travel time choices, often due to speed choice. Travel time is obvious, as increased speed is perceived to reduce travel time. The price, *P*, will likely increase with speed as fuel consumption will be higher, but hard accelerations and braking will also increase fuel costs (Noland & Quddus, 2006). While actual objective risk increases with higher speed (given road design) this may not be perceived by all individuals. Capabilities are mainly influenced by individual characteristics of the individual. However, reduced capability may lead some drivers to reduce their speed or use alternative travel modes or even forego driving completely. In-vehicle activities or distractions increase risk, again this may not be properly perceived by individuals. On the other hand, some individuals will reduce these activities when the road environment is riskier. The main implication is that in all of these factors there are trade-offs made by the driver to maximize their perceived utility.

The utility of travel may also be affected by other factors. For example, the reliability of travel (Noland & Small, 1995), convenience of inter-modal exchanges, and the comfort of various modes. These can easily be included in a general framework and might even have implications for risk taking. For example, if traffic is unreliable due to congestion, this may lead to various risk taking activities to minimize travel time. Increased comfort may cause travelers to misperceive their capability levels and affect attention levels with consequent trade-offs with risk.

This framework hopefully clarifies some of the issues surrounding risk compensation theory and leads to a generalized cost model of transportation demand, consistent with other approaches in the literature. In essence, all risk compensation implies is a trade-off between reductions in risk and increases in the consumption of other goods, primarily mobility. The model incorporates some of the other proposed theoretical frameworks within a simple unified theory, and proposes that drivers make many trade-offs that can vary based on their perceptions of the situations they find themselves in as well as their own capabilities.

One implication is that the assessment of the benefits of various risk reduction technologies and policies should not be based solely on the forecast safety improvement, but should also capture the mobility benefits that also occur; this has implications for cost-benefit analysis, discussed further below. The next section puts these ideas into context by discussing the behavioral reactions one would expect based on this theoretical framework.

4. Expected behavioral reactions to safety policies

Using the theoretical framework described above, it is possible to consider various hypothetical behavioral reactions to various safety policies, some of which have been tested empirically. Several are briefly discussed, specifically engineering and design policies, the impact of weather, policies aimed at reducing crashes among young drivers, policies to reduce driver distractions, drunk driving policies, congestion reduction policies, and vehicle fuel economy standards.

4.1. Road engineering and design policies

In an unpublished manuscript, Hauer (1999) provides a succinct summary of the current process of designing roads and the consequent implications for safety. Referring to the tradition of civil engineering, he states,

> "…they have erected a conceptual framework which cannot recognize the basic fact that people adapt to circumstances whereas inanimate matter does not…The consequence of this fundamental misconception is that speed, reaction time and similar parameters are treated as constants in all the formulae and computation that are at the root of geometric design standards." (Hauer, 1999, p. 18)

His critique is focused on the design guidance produced by the American Association of State Highway and Transportation Officials (AASHTO), the *Policy on Geometric Design of Highways and Streets*

(AASHTO, 2004). He documents instances of not modifying the guidance based on new knowledge and the latest research on how design affects safety. For example, Hauer (1999) cites numerous studies that suggest that 11 ft lane widths are superior to 12 ft lane widths, yet AASHTO (2004, p. 311) states, without evidence, that 12 ft lane widths are 'desirable'.

Previous research by Noland (2003) examined US data to determine whether various categories of road and associated lane widths had an impact on fatalities. This work concluded that, in general, wider lanes increased fatalities and various non-infrastructure related policies reduced fatalities, such as increased safety-belt use.[11] The key issue with changes in road infrastructure, such as widening lanes or adding more lanes to an existing facility, is that these have an impact on speed. Increased speed will tend to increase mobility, either by allowing faster trips, but also by encouraging more trips via induced travel effects (Noland & Lem, 2002). Thus we have a situation where increased mobility may be achieved but with increased risk from increased speeds and increases in overall travel. This contradicts the engineering assumption that increased lane-width will allow more room for a vehicle to safely maneuver; it might permit this in some cases, but the trade-off is that some individuals will use this extra space to increase their speed.[12]

An experiment was conducted in the Netherlands to assess changes in driver speeds and physical responses to a reduction in lane width (De Waard, Jessurun, Steyvers, Raggatt, & Brookhuis, 1995). This study used an instrumented car to measure speed, lateral positioning, and steering movements in response to a reduction in lane width as well as placement of gravel chippings along the road. Drivers were also wired to record physical responses, such as changes in heart rate. The overall results showed that speed was reduced with width reductions. Likewise high-frequency steering movements increased and the standard deviation of lateral positioning was reduced, implying better lane tracking of the vehicle. Likewise the physiological responses suggested an increase in the driver's mental load. The increase in steering effort (resulting in better lane tracking) is a consequence of this increase in mental load and overall reduction in speed.

A recent study that evaluated lane widths on urban and suburban arterial roads also found that widths in excess of 11–12 ft were not necessarily safer (Potts, Harwood, & Richard, 2007). The modeling done in this study, however, lacks a consistent theoretical basis, and likely suffers from omitted variable bias.[13] Mitra and Washington (2012) demonstrate how the omission of key variables can lead to bias in the results for the key variables of interest.

Recent work in the domain of urban planning has extended these ideas to consider how urban streets can be made safer. Using county-level indicators of urban sprawl, Ewing, Schieber, and Zegeer (2003) find an association between urban sprawl and increased traffic fatalities. Much of the focus is on making streets safer for pedestrians but also for motorists, primarily by designing roads that are more appropriate for urban areas, with fewer lanes and lower speeds. Ewing and Dumbaugh (2009) review much of the work in this area and conclude:

> "…the fundamental shortcoming of conventional traffic safety theory is that it fails to account for the moderating role of human behavior on crash incidence." (Ewing & Dumbaugh, 2009, p. 363).

Dumbaugh and Li (2010) conducted an analysis of traffic crashes in San Antonio, Texas. Their analysis found freeways to be safer and attribute this to access control rather than design speed. Arterial roads are found to be riskier, even when they have forgiving design elements, largely due to more traffic conflicts. Noland (2003) found similar results for arterial roads. From an urban planning perspective the conclusion is that streets in cities should not rely on standard guidance for road design that emphasizes maximizing traffic flow (and hence increasing mobility).[14]

At the other extreme of road infrastructure measures, traffic calming will reduce mobility via the mitigation of speed and making driving less comfortable. Traffic calming not only reduces speeds, but also mobility, which may have a secondary safety benefit. One technique is to change lane markings to create the perception that the road is narrower; this has been found to reduce speeds in simulator studies (Godley, Triggs, & Fildes, 2004); they also found that mental workload[15] increased with narrower lanes. Perceptual reductions in road width have the benefit of not changing objective risk levels (i.e., the clear zone remains the same), but changes driver perceptions of a safe travel speed, thus drivers slow down and overall risk is reduced. Lewis-Evans and Charlton (2006) found a similar result using a driving simulator. Of note they argue that drivers implicitly respond to the riskier environment rather than making a conscious decision to travel more slowly; they argue that this reaction is consistent with Summala's (1988) Zero-Risk theory that implies drivers only respond to risks above a certain threshold.

Overall, empirical work supports the concept of a behavioral response to changes in the road infrastructure, and this operates largely by either exchanging mobility for increased safety or restricting mobility, with the latter leading to increased safety. Conceptually traffic calming or lane width reductions are equivalent to a movement along the isoquants shown in Fig. 1.

4.2. Weather and safety impacts

Winter weather provides a good example of the behavioral responses to a change in driving conditions. Both decreased visibility and decreased road friction will tend to result in a decrease in speed (Strong, Ye, & Shi, 2010). There is also likely a decrease in total travel, depending on the severity of the winter storm; there is evidence that adverse weather, mainly rainfall events, will affect how commute trips are made (Khattak & Palma, 1997). Clearly the reduction in speed and travel is a reduction in mobility to what is perceived to be a less safe driving situation. Studies have suggested that there is an off-setting effect on actual risk. Speed reductions during snowfall have been shown to lead to reduced fatalities (Eisenberg & Warner, 2005). However, the decrease in road friction leads to an increase in less severe crashes (property-damage only and injury crashes). Evidence also suggests that driver perception of the road environment (i.e., perceived risk) and experience with winter weather can have an impact on safety. Crashes tend to be higher during the first snowfalls of a season, perhaps due to drivers not perceiving the risks properly (Eisenberg & Warner, 2005).

[11] Similar to Hauer's (1999) review, 11 ft lane widths appeared to be optimal from a safety perspective, relative to both narrower and wider lane widths.

[12] Another way to put this is that "wider, straighter, faster" is not necessarily safer (Toth, undated).

[13] This study was part of a National Cooperative Highway Research Program report, which produces guidance documents used by many transportation agencies. The study had various shortcomings, and these issues of translating empirical work to practice are discussed further below.

[14] These include the Highway Capacity Manual (TRB, 2010) and the *Policy on Geometric Design of Highways and Streets* (AASHTO, 2004).

[15] Measured using NASA-TLX (Task Load Index), (Hart & Staveland, 1988) and by steering deviations.

Eisenberg and Warner (2005) provide some interesting results on how snowfall affects safety by age group. Drivers older than 65 years had increased risk for the first snowfall event (defined as after 100 days of no snow), but their risk was less for subsequent days. Those in the 30–50 age group have the highest risk for all snowfall events. The former implies that perhaps older drivers have less ability to control their vehicle during snow but compensate (by driving less) on subsequent snow days. The 30–50 age group may be more at risk during subsequent snow days because they must engage in more non-discretionary travel (such as work trips); that is, the value (or motivation) of the trip is greater and they balance this against the increased risk.

Despite any off-setting reductions in mobility, it is likely that total risk is still larger when severe weather events occur. A meta-analysis of studies from 1967 to 2005 found that crash risk was higher (Qiu & Nixon, 2008). Thus severe weather represents a leftward shift in the isoquants in Fig. 1, a reduction in mobility and safety. Any technology that makes driving easier in severe winter weather conditions (e.g. studded tires), can potentially maintain mobility and increase safety (Elvik, 1999).

4.3. Age and experience

The crash risk faced by younger drivers, especially young male drivers can also be evaluated within this framework. In general, there are several reasons for regulating the driving of younger drivers. First, they may not have acquired the skill and experience to adequately handle a vehicle, especially under stressful situations (Deery, 1999). Second, they may not have fully developed cognitive abilities to properly perceive risks (Shope, 2006), and third, they may be overly confident in their own driving skills (Deery, 1999). These issues are traditionally handled by regulating the age at which individuals are allowed to drive and requiring driver education and training prior to granting a license. Clearly, given the crash rates of younger drivers, these programs have not adequately addressed the problem. Enhanced training, which increases capabilities (or driving skill and confidence) may actually encourage some drivers to take additional risks, especially if their perceptions are not correct, as would be the case with younger drivers.

Graduated licensing programs, which specify conditions on when and where new drivers can drive, are becoming increasingly common in the US. These are a means of restricting mobility during a given training period and appear to be successfully reducing risk (Williams, 2005).[16] Some young drivers appear to defer receiving a license because of the greater restrictions imposed once a license is obtained; Shope, Molnar, Elliott, and Waller (2001) found this to be the case in Michigan. In essence a graduated license program both increases the cost of learning to drive and also decreases the mobility benefit (or utility) obtained once the initial license is granted. Chen, Baker, and Li (2006) found that the more comprehensive a graduated licensing program is, the greater the reductions in fatalities for 16-year old drivers. The most comprehensive programs include a 3-month waiting period for receiving a license, nighttime driving restrictions, passenger restrictions (such as not allowing other children to be in the car, without parental supervision), more than 30 h of supervised driving and a minimum age of 16 before receiving a license. All these components make it less attractive for some young drivers to obtain a license. Therefore, these programs likely reduce mobility and thereby reduce risk, but also increase the cost of obtaining a license, and may also improve the capabilities of young drivers. Thus, it is not surprising that crash and fatality reductions have occurred.

[16] Williams and Ferguson (2002) explicitly state that "graduated licensing represents a compromise between safety and mobility" (p. ii9).

Risk tends to increase as drivers age, mainly due to reductions in physical and cognitive functions. Compensatory behavior occurs among older drivers as many reduce their mobility voluntarily. Ross et al. (2009) have demonstrated that older drivers who are more at-risk, measured using various cognitive and driver performance tests, will tend to avoid driving (based on a 5-year longitudinal study). However, this compensatory reduction was not sufficient to reduce crash risk, implying that some interventions may still be required to reduce risk, such as more frequent testing and licensing above a given age, which would increase the cost of driving (and therefore reduce the likelihood that some older people will continue to renew their license).

Policies aimed at different age groups must, therefore, be designed to recognize any cognitive limitations or misperceptions of risk. The success of graduated licensing suggests that reducing mobility and decreasing the motivation to drive (e.g. by restricting passengers) among youth has been a successful policy. Restricting mobility for aging populations is a more difficult problem, probably best solved by providing different travel options for older people who can no longer safely drive.

4.4. Distraction and fatigue

One area of growing concern among road safety professionals is the impact of in-vehicle distractions on driver performance and safety. In particular, cell-phone and texting have been demonstrated to increase driver error (Caird, Willness, Steel, & Scialfa, 2008; Owens, McLaughlin, & Sudweeks, 2011). Many countries (and states in the United States) have passed legislation making cell-phone use and texting illegal while driving.

The Naturalistic Driving Study funded by NHTSA tracked information on 100 vehicles with detailed video and other data collection for one year. As reported by Klauer, Dingus, Neale, Sudweeks, and Ramsey (2006), one of the primary results of this study was the role that inattention (or distraction) plays as a causative factor in crashes and near-crashes (the latter being data that is not possible to collect except via these intensive video data collection techniques). They found that drowsiness and engagement in secondary tasks (within the vehicle) significantly increased the odds of a crash or near-crash event. Inattention, and specifically those distractions that led to eye-glances away from the forward road of greater than 2 s were associated with more crashes and near-crashes (although it is stressed that some eye-glances, for example, to view side and rear-view mirrors, reduce risk, and may also be associated with a safer driver). Inattention was also found to be larger for younger and less-experienced drivers. Interestingly, drivers were found to be less drowsy when driving conditions required greater attention, perhaps suggesting some compensating behavior.

A driving simulator study conducted by Horberry, Anderson, Regan, Triggs, and Brown (2006) found that there is compensatory behavior when drivers are distracted by in-vehicle visual and auditory distractions. These included following instructions to adjust an entertainment system and answering a set of questions (to simulate a phone conversation). Tests of external distractions (e.g. road clutter and billboards) were also conducted. Differences in the average speed were measured, with speeds decreasing when respondents were distracted, whether from external stimuli or internal tasks. This study, of course, does not answer the question of whether the net effect leads to greater risk taking; this likely depends on the amount of off-setting speed reductions and the variability in response from different drivers, perhaps caused by differences in their ability to accurately perceive road risks. Young and Salmon (2012) point out that not all distractions lead to errors on the part of the driver and not all errors lead to crashes; the role that the road system plays in controlling the relationship between distraction and errors is not fully understood. Driver errors include those made in observation and recognition of hazards, errors in decision making, and errors in actions taken (including the recovery response to errors).

Laws prohibiting cell-phone use and texting in vehicles are intended to reduce distraction. These would increase the cost of engaging in this behavior (due to receiving a citation) and would likely lead to a reduction in risk taking. These laws are recent and as of this writing have not been evaluated for their effect on crashes and casualties, although there is evidence that use of handheld cell phones is reduced (McCarrt, Hellinga, Strouse, & Farmer, 2010).

4.5. Policies for driving while intoxicated

Policy makers have long been concerned with finding ways to reduce the incidence of driving while intoxicated. Drunk driving has long been associated with increased crash risk, both to those who are intoxicated and to innocent victims. Applying the theoretical framework, we would expect that intoxication would lessen the capability of drivers, and thus increase their relative risk. Some drivers may consequently exchange the increased risk for a reduction in their mobility, by not driving. From this perspective, one could argue in the extreme case that intoxication has no effect on overall utility if proper trade-offs are made and if perceptions of capability and risk are accurate. These latter assumptions are likely to be incorrect, as by its very nature, intoxication will distort perceptions of individual capability and risk. Most approaches have sought to increase the cost associated with intoxication, either by increased fines, revocation of licenses, sobriety checkpoints, and reduced allowable blood alcohol levels (Voas, Tippetts, & Fell, 2000). These policies also will reduce mobility, but overall have been found to be effective.

4.6. Congestion and safety

Increased congestion is often assumed by policy makers to increase risk. However, congestion reduces speeds which may reduce risk, at least for more severe accidents. Efforts to reduce congestion via increased road capacity may only generate more traffic and more vehicle interactions, which might be of lower severity (Noland & Lem, 2002). Research that has examined the relative severity of accidents in congested and uncongested flows suggests that while congested traffic may lead to an increase in less severe accidents, free-flowing traffic may result in more severe accidents (Zhou & Sisiopiku, 1997). While theory can easily suggest that this is the case, not analyzing the factors associated with both severe and less severe accidents may miss this detail. Policy may be distorted without careful analysis of the effects of congestion, especially in built up areas. Recent research suggests that more dispersed development and larger roads (built to reduce congestion) are associated with increased risk (Ewing & Dumbaugh, 2009).

4.7. Vehicle fuel economy standards

There has long been a debate in the US over the safety of smaller (more fuel efficient) cars. It has generally been assumed that larger and heavier vehicles are safer (Evans, 1984; Evans & Frick, 1992; Kahane, 1997; National Research Council, 2002).[17] But this misses the behavioral element of how these larger vehicles may affect those driving smaller cars as well as how the drivers of larger cars may change their behavior (Wenzel & Ross, 2005). Drivers of smaller vehicles may take more protective actions, such as traveling at slower speeds and increasing gap distances if they are more cautious of interactions with larger vehicles. Likewise, those in larger vehicles that are perceived to be safer may drive more aggressively.[18] Furthermore, since the original US fuel economy regulations in the 1970s, all vehicles have seen an overall improvement in their safety (Noland, 2004) making it difficult to disentangle the effect of changes in size on safety.

5. Linking theory to empirical modeling

In conducting empirical development of safety models, most analysts are concerned with developing more effective methods for saving lives and reducing crashes. Therefore, a primary objective in any analysis is to provide information to improve decision making and on the design of procedures, regulations, and policies that can save lives and reduce crashes. This might occur via studies that evaluate specific policies, test hypotheses, or forecast the effects of changes. All these have a role in safety analysis and evaluation, but not all methods are suitable for these approaches.

One of the major problems with the use of models is the desire to calculate deterministic crash modification factors (CMF).[19] These are the parameter estimates from models and are used to forecast the reduction in crashes from a specific change, typically in the road infrastructure. The methods used to calculate these range from simple "before and after" studies, comparison group studies, and empirical Bayes estimates, which can control for regression to the mean (Shen & Gan, 2003). All suffer from various problems. One of the main problems is the lack of control, in most studies, for other factors that may affect crash rates. Therefore, the effectiveness of certain interventions will typically be overestimated.

CMFs are typically used to prioritize budgets for engineering treatments and to conduct cost/benefit analysis of the overall effects. However, in practice there is a tendency to ignore the potential errors surrounding the estimation of these factors. At a minimum, reported results should include confidence intervals surrounding any parameter estimates allowing the associated error (both positive and negative) to be carried forward into further analysis.[20]

One major flaw in many published works is the lack of a theoretical foundation for specifying models. Within the framework discussed here we would expect at a minimum for any study to consider the context of a road safety policy, in particular what population is likely to be affected by the change? What are the demographics of the surrounding population? What type of vehicles use the road? What other policies are being implemented concurrently? Most studies in the literature, especially those that examine road design, ignore this larger context and tend to focus on narrowly defined changes, thus they will suffer from omitted variable bias (Mitra & Washington, 2012). Hauer (2012) grapples with these issues in the context of how CMFs are estimated and provides a simple example of how variation in lighting conditions

[17] Greene and Keller (2002) in a dissent from the National Research Council (2002) study discuss some of the problems with the analysis of data to determine these effects.

[18] Aggressive driving behavior is more common among men, especially younger men; they also tend to drive vehicles with more horsepower (Krahé & Fenske, 2002; Shinar & Compton, 2004).

[19] Also known as accident modification factors or AMFs.

[20] Elvik (2003) identifies various policy constraints on the effective use of cost/benefit analysis to set road safety policy. One in particular he defines as a "social dilemma", where societal benefits do not necessarily accrue to individuals. A case in point is speed limit reduction where individuals may not benefit despite societal safety benefits.

can affect a policy of increasing illumination on a road, and how ignoring this variation leads to inaccurate results.

In the published literature it is common to find articles that analyze a crash dataset, with many independent variables, and then simply describe what is statistically significant, without any prior consideration of theoretical expectations. Lovegrove and Sayed (2006) provides a good example. Sometimes these articles ignore the far more important result as to what *is not* statistically significant. Frequently, those variables that are not statistically significant will be removed from the final models presented, thus potentially losing important results. Noland and Oh (2004) review some recent articles and highlight some of the buried results. A focus on theory would help the authors and their readers to better evaluate the meaning of the statistical models and provide guidance for understanding the importance of both significant and insignificant results.

The study of crashes should be inferential and seek to test hypotheses based on a theoretical model. Engineering tends to focus on deterministic goals and deterministic modeling, primarily for forecasting the effects of various changes. Inferential hypothesis testing conflicts with the inherent epistemology of engineering sciences that seeks to build models to forecast changes from a given effect. The latter is certainly appropriate in many fields of engineering, however, when dealing with human behavior more stochastic approaches need to be taken.[21] The engineering approach has resulted in the development of CMFs that are deterministic and then used to forecast outcomes (AASHTO, 2010).

Most studies now use more sophisticated statistical methods and Lord and Mannering (2010) provide a succinct review of these. Specifically, count models that correctly account for the distributional properties of most accident data, are being increasingly applied, and are generally recognized as the correct modeling approach in most cases. Bayesian techniques are now considered the standard approach to estimating safety models, particularly empirical Bayes models to estimate CMFs (Persaud & Lyon, 2007).

One of the flaws in many older studies is the use of simple ordinary least squares regression techniques that assume normality in the data and neglect the statistical properties of the data. Another dated technique is the analysis of simple before and after studies applied to specific engineering interventions. These often suffer from "regression to the mean" effects, i.e., endogeneity bias in that the selection of interventions was not independent of the crash history at each site (Persaud & Lyon, 2007). These issues are now generally well recognized, but the misinformation and conclusions derived from older studies can linger for many years; below we discuss how poor studies from the past are being used in the development of the new *Highway Safety Manual* (AASHTO, 2010).

Another issue is the ability to control for various trends and policies that affect road crashes that are not of key interest in the study being conducted. For example, studies of road engineering interventions may typically not consider changes in safety-belt usage, local demographic make-up, medical care improvements, or economic cycles when evaluating the effect of the change. These other effects may often be far more important than road engineering changes and may even mask negative effects associated with some of these changes (Noland, 2003). Some studies are unable to control for all changes, normally due to data limitations or the design of the study. Before and after studies, or those studies without a cross-sectional component to the data are typically unable to account for other policy changes. While these more limited studies can play a role in some circumstances, care must be taken with how the results are interpreted and suitable caveats must be understood. Linking these models to the theoretical framework discussed above is necessary to provide guidance on empirical analysis, such as what variables should be included in any empirical model.

More advanced techniques, such as empirical Bayes are designed to control for other factors by use of a comparison group of untreated sites. But as Persaud and Lyon (2007) note, the application of this method, if not done with care, can still generate invalid results. For example, they show how one must consider the effect of a treatment on different types of crashes, as there may be differential effects (e.g. red-light cameras are known to reduce right-angle crashes, but increase rear-end crashes). All crashes are typically counted without considering differential effects on fatalities versus property-damage only crashes. Specifying the correct comparison group is always an issue as is controlling for all the other factors associated with crashes that may change over time. Full Bayesian approaches are also receiving some attention and can provide some benefits to understanding, particularly in providing an estimated *credible interval* rather than a confidence interval on estimates (Persaud, Lan, Lyon, & Bhim, 2010). This provides a range of estimates for a given effect rather than a point estimate.

Panel regression approaches are capable of controlling for other policy changes as well as for unmeasured effects. These require aggregation of data for a given data unit, such as a region, and time-series data. Aggregation of data introduces other issues but has the benefit of allowing sufficient numbers of rare events to be captured within the dataset, for example over a one-year time period. The level of aggregation is also important. Larger regional units allow one to fully capture a sufficient count of fatal accidents that smaller spatial units may not due to the rarity of these events.

One problem with those studies that use smaller units of aggregation (e.g. a series of links on a highway, for one week) is the need to aggregate crash data with different levels of severity – primarily fatal and injury-only crashes.[22] This inherently assumes that the behavioral and engineering mechanisms that lead to fatal crashes are the same as those with less severe outcomes. There could be instances where theory may suggest very different mechanisms involved with different severity outcomes. For example, an area with very high speed traffic may have no pedestrian fatalities and injuries, due to pedestrians being fully aware of the risk, while an area with slower traffic may suffer from more pedestrian injuries. Care must also be taken to disaggregate the aggregate data not only into different levels of severity, but different types of crashes, suggesting there are benefits to large regional aggregate analysis. Again, theory is the best way to determine the most suitable empirical design.

6. Use of empirical results

There are two reasons to estimate crash models. One is to understand what policies, design, and programs might be effective at reducing crashes. The other is to develop CMFs that are then used in cost/benefit analysis (CBA) to justify expenditures on road design changes or policies. The former only requires one to inferentially test hypotheses as to whether a given effect is statistically significant; the latter requires a coefficient value to be used in CBA, which

[21] This point is likewise emphasized by Hauer (1999) "Engineers tend to base design procedures on the foundation of physical laws, mathematics and the empirical knowledge of the properties of metals" (p. 15), all of which are deterministic in nature.

[22] The quality of data associated with different severity levels can also vary. Most countries track fatality data very well, while less severe categories tend to be less complete.

can often be more problematic. This section focuses on the problems with the use of CMFs as currently derived and used in practice.

A major problem is the use of statistical coefficient estimates as point values. It is assumed that these are deterministic with no error bands. While standard errors are sometimes reported, they are needed and can be used to provide a range of inputs into a CBA analysis. Most CMFs are also based on total crashes, not distinguishing the severity level of casualties, or for that matter the type of crash.[23] Severity levels are needed to properly value the cost of a crash. Also, many of the CMFs estimated likely are biased, either due to regression to the mean or omitted variables, further questioning their use without a full understanding of these caveats (Mitra & Washington, 2012).

Hauer (2012) provides a useful critique of the new *Highway Safety Manual*.[24] His main conclusion is that CMF's estimated in one context may not apply to another context. This is self-evident if one considers that most of the models developed omit key control variables. Another problem is that the standard error of results may not be reported, again leading to a deterministic view of the results. The *Highway Safety Manual* does report the standard error for some CMF's, but not for all of them.

One area that has long been of concern is the safety performance of two-lane rural roads.[25] The CMF for lane width on rural two-lane roads does not report any error bounds (see Table 10-8, p. 10–24, AASHTO, 2010). The CMFs reported are based on annual average daily traffic of less than 400 and greater than 2000 vehicles per day, with a linear formula provided to interpolate between the two. Table 1 displays the CMFs for the two boundary cases, omitting the formula for interpolation. Of note, the CMFs are only for certain crashes deemed to be more likely to be associated with narrower lane widths. These are single-vehicle run-off-the-road, multiple-vehicle head-on, and both opposite and same direction sideswipe crashes. These are estimated to be 57.4% of all crashes on rural two-lane roads (see Table 10-4, p. 10–17). There is no explanation given as to why just these are assumed, other than the feeling that they are associated with narrower lane widths.

Several features of this CMF are clearly problematic. First, no standard errors are shown in the table, so the analyst is unaware of how good these estimates are. Second, no information is provided on whether there are statistically significant differences between the estimates; especially for the range of CMFs for less than 400 vehicles per day, and between 11 ft and 12 ft lane widths for greater than 2000 vehicles per day. Likewise, no explanation is given as to why one would assume a linear interpolation as a function of vehicles per day, rather than a non-linear or threshold effect; Persaud and Lyon (2007) note that the relationship of traffic volume to crashes is non-linear. More importantly, no context is given for what confounding factors were included in the models on which the estimates are based. The reader is referred to two studies that these parameters are drawn from, Zegeer, Deen, and Mayes (1981) and Griffin and Mak (1987). Both are dated for a guidance document published in 2010.[26] Only one of these is an archival publication, readily available for review.[27] The HSM gives no clues as to how these studies were used in deriving the CMFs.

Table 1
Crash modification factors from the highway safety manual (AASHTO, 2010).

Lane width CMF	<400 vehicles/day	>2000 vehicles/day
9 ft or less	1.05	1.50
10 ft	1.02	1.30
11 ft	1.01	1.05
12 ft or more	1.00	1.00

Of note is that other more recent work has questioned the underlying assumption that larger lane widths are beneficial for safety. Hauer (2005) has questioned the functional form of some studies that concluded that wider lanes are better. In particular, Hauer suggested there should be an optimal lane width that minimizes risk. Those functional forms that are empirically estimated tend to imply that an infinitely large lane width has a linear effect on reducing risk. While not specific to rural roads, other empirical work has found that 11 foot (3.35 m) lane widths are likely optimal and that larger lane widths increase risk (with different effects based on the category of road) (Noland, 2003). Likewise, Milton and Mannering (1998) found that narrower lane widths (below 11.5 ft) reduce crash frequency. Theoretically one would expect that behavioral adaptation might lead to higher speeds as lane widths increase, off-setting any benefits from more space for vehicles.

Zegeer et al. (1981) actually comes to the conclusion that there is little difference between the safety effect of an 11 ft and a 12 ft lane width. However, it is not clear from the *Highway Safety Manual* how the results of Zegeer et al. (1981) were used in development of the CMFs (see p. 10–23). Zegeer et al. (1981) contains only a simple cross-tabulation of various crashes by lane width (and shoulder width) for a sample of rural highway links. No statistical tests are reported for the cross-tabulations and no multivariate analysis was conducted on the disaggregate data. Thus, it is hard to see how this study (perhaps state-of-the-art in 1981) is useful for informing current practice.

Griffin and Mak (1987) is also methodologically challenged and it is also not clear how the results in Griffin and Mak (1987) are related to the CMFs developed in the *Highway Safety Manual*. Griffin and Mak (1987) analyze rural two-lane road crash rates in Texas. The analysis consists of calculating crash rates disaggregated by various roadway widths and average daily traffic volumes, and these are presented in a cross-tabulation. The cross-tabulation cells for a given average daily traffic volume then serves as a basis for a linear regression of the crash rate in the cell versus the lane width categories, of which there are only six. That is, this study is based on a regression with $N = 6$ for four ranges of traffic volume using data that is highly aggregated. It is disturbing that such an invalid analysis would serve as the basis for developing CMFs and policy on road safety!

A search for further clues to the source of these CMFs can be found in Harkey et al. (2008). This was a study that reviewed and evaluated various CMFs, including the input of an expert panel on the quality of prior research and to build consensus on the best CMFs. Harkey et al. (2008) cites the source of the CMF for two-lane rural road lane widths as Harwood, Council, Hauer, Hughes, and Vogt (2000) and Harwood, Rabbani, Richard, McGee, and Gittings (2003), in addition to the two previously mentioned studies.

[23] For example, nighttime crashes should be distinguished from total crashes if the CMF is for lighting fixtures.

[24] The Highway Safety Manual is being developed as a companion to the Highway Capacity Manual that road designers can follow to improve safety.

[25] These account for a disproportionate amount of total accidents. Over one-third of 2010 annual fatalities in the US occurred on rural roads, omitting interstates and principal arterials (derived from FARS data: http://www-fars.nhtsa.dot.gov/Main/index.aspx).

[26] Hauer (1999) discusses a 1944 reference recommending wider lanes that was cited up until 1990 in succeeding versions of AASHTO's *Policy on Geometric Design of Highways and Streets*. The 1994 version drops the citation but keeps the conclusion with no reference at all. Thus is conventional wisdom propagated.

[27] Griffin and Mak (1987) is available only as a TRB pre-print and only at one library in the United States through inter-library loan.

Harwood et al. (2000) was a study that included estimation of models to determine relationships between crashes and various geometric design features. These models used data based on road segments for several states and were estimated with negative binomial regression models. They likely suffer from omitted variable bias (Mitra & Washington, 2012) but are a substantial improvement over earlier work. However, the actual CMFs for two-lane rural roads do not seem to bear any relation to the modeling work, as both Zegeer et al. (1981) and Griffin and Mak (1987) are again cited as the source for the CMFs, the former for AADT in excess of 2000 vehicles/day and the latter for AADT below 400 vehicles/day. Harwood et al. (2003) does not add anything new, but merely restates the CMF from Harwood et al. (2000). These were viewed as adequate by the expert panel convened for Harkey et al. (2008). This largely confirms the antiquated source of the CMF for two-lane rural road lane widths used in the HSM.

A critique of the expert panel review process is supplied by Washington, Lord, and Persaud (2009). The authors of this paper were members of the expert panel that reviewed CMFs for Harkey et al. (2008). They criticize the use of expert panels in finding consensus on CMFs, in particular they note that "…the HSM expert panel process is subject to social interactions and the collaborative goal of reaching consensus, which may lead to bias." (p. 105). Consensus tends to mask the uncertainties in CMF estimates and the shortcomings of some of the research being reviewed. Harwood et al. (2000) also used an expert panel to reach consensus on the CMF for two-lane rural roads, and likely suffered from these same issues.[28]

Hauer (2011) provides a different critique of CBA in analysis of road safety projects, based on the uncertainties involved with estimating the value of a statistical life, as well as the difficulties of estimating the value of time. It is this trade-off that is critical; Hauer (2011) demonstrates that in some cases the value of one-hour of life is less than the value of one-hour of delay based on existing estimates. As he puts it "It is absurd to think that when deciding on how to spend public money, travel time and time being dead should have the same value" (p. 153). His critique further questions the suitability of discounting time and lives saved, as well as the selection of a discount rate.

Holz-Rau and Scheiner (2011) suggest that projects that reduce travel time (e.g. by increasing speeds) can lead to more fatalities. They imply based on an analysis in Germany, that these issues are often hidden in cost-benefit analysis, without highlighting that a trade-off is being made between time and lives. This is despite official policy that prioritizes safety over speed. They also estimate that the value of life is lower than the value of reducing travel delay.

The trade-off between risk and mobility also implies that many safety improvements result in a mobility increase, often by facilitating greater speeds with less risk. This greatly complicates a CBA as one must determine the allocation of benefit to risk reduction and to mobility improvement. At a minimum, these issues must be explicitly recognized, but as this discussion has highlighted, a far more serious problem is the use of invalid studies to develop CMFs.

7. Conclusions

The path from theory to empirical modeling to application in practice is filled with potholes. Much of the theoretical debates are not clearly resolved, although there is a consensus that behavioral adaptation occurs and theory can provide guidance on when this is likely to be a large effect. The proposed theoretical framework is intended to clearly provide a grounding within transportation economics of how to understand the motivations of travelers (i.e., their utility maximizing behavior) and how trade-offs are made between risk and mobility, as well as other attributes that influence transportation choices. Much of the empirical modeling of road safety tends to not be grounded in any theoretical framework and it is hoped that analysts will consider these theoretical issues when conducting empirical analysis. This will provide guidance on which variables should be in road safety models and avoid or minimize any omitted variable bias.

The lack of theoretical rigor in empirical work is compounded by a hangover from much of the older literature, up until at least the late 1980's, using outmoded statistical techniques, and the conclusions from these studies persisting in formal guidance documentation, such as the *Highway Safety Manual*. Some of this is due to the use of expert panels to provide consensus on existing knowledge. While empirical methods have improved tremendously in the last 20 years, there is still much knowledge needed to fully understand how various components of road design, regulations, and policy affect both risk and mobility.

The publication of the *Highway Safety Manual* in 2010 poses new challenges and opportunities. The challenge is that this may codify incorrect CMFs for many decades to come. The opportunity is that theoretically grounded and more sophisticated analysis can improve the CMFs, including an understanding of the error associated with them, and lead to better decision making. One issue that is incumbent upon all researchers is to convey the complexity of these issues to decision makers. This is not necessarily easy as there is a tendency for decision makers to want simple answers without the subtleties that may be involved by focusing on trade-offs, uncertainty and error bands.

This paper has highlighted one of the key trade-offs, which is between risk and mobility, and hopefully an improved understanding will provide insights on political decisions and the implementation of policy. The major conclusion is that road safety studies and the guidance developed from these must be based on a theoretical foundation that considers the behavioral reaction to a policy change.

[28] Harkey et al. (2008) does not provide any additional information on the discussions of the expert panel.

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