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• Safety Culture from an Interdisciplinary Perspective: Conceptualizing a Hierarchical Feedback-based Transportation Framework

Anjala S. Krishen
Corresponding Author
University of Nevada Las Vegas
anjala.krishen@unlv.edu

Pushkin Kachroo
University of Nevada Las Vegas

Shaurya Agarwal
University of Nevada Las Vegas

S. Shankar Sastry
University of California, Berkeley

Masha Wilson
MBW & Associates, LLC

Abstract

Given the colossal issue of traffic accidents causing serious injuries, fatalities, and traffic congestion in the United States, the current article introduces a feedback safety model that utilizes and combines disparate data sources and allows for model-based action to alleviate the problems. This feedback model will serve two purposes: (1) it will provide an overarching view of safety culture that incorporates fundamentally distinct data sources; and (2) it will aid in the development of targeted messages and control actions at various levels, especially to the highest-risk public segments, which can highlight the risks of unsafe driving as well as increase perceived importance for traffic safety. In order to develop this model, the article begins with the issue of distracted driving in the main study. The basic premise of the argument is that drivers who are distracted are more likely to be unsafe (i.e., the behavior is normally augmentative) and that safety is a *culture*, not a concept. In essence, curbing distracted driving should lower vehicle-based accidental deaths. We will then argue for an overarching safety culture framework to lower distracted driving from a holistic perspective through gathering multiple data sources and developing targeted communication mechanisms.

Introduction

After six consecutive years of declining motor vehicle crash-related fatalities, their number increased by 3.3 percent in 2012, from 32,479 fatalities in 2011 to 33,561 in 2012 (National Highway Traffic Safety Administration 2013). The number of traffic-related injuries saw a similar increase from 2.22 million in 2011 to 2.36 million in 2012; additionally, there was a 3.1 percent increase in the total number of police-reported traffic crashes between 2011 and 2012. High-risk behavior and high-speed mobility combine to create this externality of the automobile industry (Williams and Haworth 2007). To make matters worse, when individuals are faced with highly familiar activities such as driving, research shows that they tend to underestimate the possibility of a negative outcome (Douglas 1985).

Today, sustainable and reliable transportation development is one of the most important and essential investments made by any government. Transportation and infrastructure affect the financial and social life of both individuals and society as a whole and plays a critical role in the development of a society's overall economy (Shang, Tjader, and Ding 2004). Our research premise is that to promote a transportation safety culture, there must be a feedback loop between infrastructure investments and ideas and individual transportation safety information. Improvement projects should be based on safety information that, while it may be currently collected, does not often serve a purpose in terms of planning appropriate and solution-oriented approaches to infrastructural modifications. Unfortunately, safety of transportation systems is one of the major challenges today. Some of the characteristics that are traditionally related to safety of any system include guidelines, audits, training programs, quality checks and assurances, and operating procedures. However, research indicates that the safety of a large and interconnected system such as a transportation network may not only depend upon direct factors but also on indirect factors such as organizational design and practices. Hence, research exploring the relationships between safety, workplace organization, and technology use in the transportation systems context is needed. Thus, safety as a cultural entity in transportation systems must be studied and researched.

Given the issue of traffic accidents causing serious injuries, fatalities, and traffic congestion in the United States, the current article introduces a feedback safety model that utilizes and combines disparate data sources and allows for model-based action to alleviate the problems. This feedback

model will serve two purposes: (1) it will provide an overarching view of safety culture that incorporates fundamentally distinct data sources; and (2) it will aid in the development of targeted messages and control actions at various levels, especially to the highest-risk public segments, which can highlight the risks of unsafe driving as well as increase perceived importance for traffic safety. In order to develop this model, the article begins with the issue of distracted driving in the main study. The basic premise of the argument is that drivers who are distracted are more likely to be unsafe (i.e., the behavior is normally augmentative) and that safety is a *culture*, not a concept. In essence, curbing distracted driving should lower vehicle-based accidental deaths. We will then argue for an overarching safety culture framework to lower distracted driving from a holistic perspective through gathering multiple data sources and developing targeted communication mechanisms. Research shows that targeted communications of social marketing causes can be very effective, such as health-related interventions (Block and Keller 1995) or taxation perceptions (Krishen, Raschke, and Mejza 2010).

This article proposes a new unique methodology to study and quantify safety culture in various types of transportation agencies. In this article safety culture is treated as a latent variable, and then a feedback-hierarchical-multilevel model shows that safety culture can be analyzed and quantified at various levels. The main contribution of this article is that it uses latent variables in a hierarchical setting to utilize big data and build models at different levels. Different layers of these models are then abstracted together at a higher level. Salient features of the proposed model are as follows:

> Different layers of modeling
> Feedback mechanism
> Comprehensive multiscale modeling
> Use of latent variables
> Use of dynamic as well as static models in a single framework

Previous studies that have investigated this problem are largely based upon a single model approach. One such study was conducted by the Federal Motor Carrier Safety Administration (Pratt 2003) to identify an hours-of-service focus on establishing certain regulations on commercial drivers. Another study based on a single-model approach on commercial truck drivers and safety-related issues was performed by

(Arboleda et al. 2003). These examples represent just part of an overall safety culture assessment framework proposed in our article. Another piece could be the effectiveness of seat-belt campaigns organized by various DOTs and the effect of seat-belt usage in injury reduction (Agarwal et al. 2013). All of these heterogeneous data could be fused together and modeled in a hierarchical fashion to assess the safety culture in each organization and provide an overall industry view. Hence our methodology is inherently different from the ones proposed earlier and a novel contribution to the field.

Literature Review

Safety Culture

The concept of safety culture originated in its application to organizations; research shows that both individual and workplace environmental components serve as important factors. Watson et al. (2005) show that trust, safety norms, management safety values, safe work environments, and at-risk behavior all factor into increases in safety culture. In an attempt to curb vehicle-related accidental deaths, several governmental organizations are reaching out to academia in search of interdisciplinary frameworks to explore safety culture as it relates to transportation (Institute of Transportation Engineers 2013). For example, the American Automobile Association (2007) introduced a traffic safety culture index (also often named the safety culture climate) and through surveys of the general public concluded that several important factors (many of which are based on driver attitudes) contribute to lack of safe behavior. Girasek (2012) argues that traffic safety culture has five major components, namely priority, dissatisfaction, accountability, engagement, and social norms. Developed through a driver survey, her modified model consists of five key individual items: (1) Traffic safety is valued; (2) individuals engage in behaviors that promote traffic safety; (3) policies that promote traffic safety receive broad public support; (4) traffic safety is monitored; and (5) social institutions are held accountable for traffic safety. A subsequent study finds that gaining public support for traffic safety remains a cultural challenge in the United States (Girasek 2013). In essence, safety culture as a measurable construct is still in its infancy (Naevestad and Bjornskau 2012). These authors also indicate that unsafe driving practices occur more in younger drivers, and that demographic factors are found to be predictive of distracted driving also.

Recently, organizations and governing bodies are beginning to focus on the concept and terminology surrounding the definition and embodiment of "safety culture," using this term to capture the essence of safety as a whole in a system. This idea alludes to a shift from focusing on individuals and direct accident-causing factors to organizational and indirect factors related to safety, a movement from studying the problem as a collection of issues to studying it from a systematic perspective. The term "safety culture" was coined in the aftermath of the Chernobyl disaster. As such, safety culture is a novel way of formalizing the processes involving risk management and mitigation in organizational and other complex system networks. Safety culture research highlights some of the behavioral practices that might lead to accidents in high-risk sociotechnical systems. Such collective research might also prove to be useful in the development of risk mitigation strategies and serve as a complement to the current safety assessment practices (Pidgeon 1991).

In general, large organizations are complex and difficult to understand, and are therefore more prone to failure in terms of organizational practices to prevent accidents in safety-critical systems (Grabowski et al. 2010). Safety culture is believed to be an important factor regarding operational safety. Some of the common features of an adequate safety culture include proper organizational communications, appropriate organizational learning, and a commitment from senior management to safety (Sorensen 2002). A safe culture is often seen as a well-informed culture that is created by an effective reporting structure, within which the behavioral guidelines are clearly explained and followed (Reason 1998). For this reason, the formation of a proper safety culture is an important determinant to the mitigation of latent factors that lead to disasters in complex interdependent networks of systems.

Grote and Kunzler (1996) propose a sociotechnical systems approach, termed Total Safety Management, in agreement with current models of quality assurance. This concept underscores the importance of organizational design and safety culture that are normally assumed to have an indirect effect on the safety of the overall system. Sorensen (2002) discusses the evolution of the term "safety culture" and the perceived relationship between safety culture and safety of operations in nuclear power generation as well as the realms of hazardous technologies. Reason (1998) analyzes theoretical and practical aspects of achieving a safe culture. In particular, some of the discussion points include reasons that an unsafe culture is more likely to be involved in organizational rather than individual accidents,

such as (1) pathological adaptations; (2) recurrent accident patterns and the role of cultural drivers; and (3) whether a safety culture can be engineered. Grabowski et al. (2010) explore the connection between safety culture and performance in complex safety-critical systems. Moreover, Grabowski and colleagues investigate a methodology that can provide early warning of hostile events by identifying leading indicators (LIs) of safety that have a positive correlation with safety performance. Wiegmann et al. (2004) summarize and integrate various studies that define and analyze safety culture along with the interrelated concept of safety climate. Such studies seem to have general disagreement pertaining to the definition of safety culture as well as the interplay or relationship between safety culture and safety climate. In doing so, Wiegmann et al. provide a list of key organizational indicators that are predictive of safety culture along with various methods that can be used to assess these factors. Sachon and Paté-Cornell (2004) propose a model that helps to determine the strategy for optimal budget allocation for the development of new technologies and safety-critical systems. Their research suggests that decomposition of the system's development process into multiple development subprocesses or modules can aid in the formation of designing multiple projects based on their criticality. Using this risk analysis approach, the balance between probabilities of development and operational failures can be established, enabling decision makers to allocate optimal budgets.

In addition to the issue of developing a safety culture, the prioritization and selection of critical transportation projects from several competing projects comes under a multi-objective combinatorial optimization (MOCO) problem. Joshi and Lambert (2007) develop a methodology for integrating equity metrics with traditional metrics, for planning and prioritization of large- scale transportation projects. This methodology is helpful to planners and managers in visualizing and comparing measures of the distributed equity along with cost-benefit tradeoffs.

The metric, technology readiness level (TRL), is a measure of maturity of an individual technology. Several concerns may arise when this measure is taken from an individual technology and deployed for a system involving interplay between multiple technologies that are integrated throughout the system. Ramirez-Marquez and Sauser (2009) propose a system-focused technique for managing a system developmental life cycle in an effective and efficient way. They define a system readiness level (SRL) that aids in determining the current and future readiness of a system. SRL index incorporates both the current TRL scale and the concept of an integration readiness level.

Data Mining, Big Data, Complex Networks

With the advent of modern electronics, which include inexpensive ubiquitous sensing, society is faced with massive amounts of data to process. The data contains information that should enable firms to make optimal decisions. However, methods by which to extract this information are not easily evident. There are many techniques that are used in data mining of big data (Ratner 2011). Some techniques come from the area of multivariate analysis such as regression, principal component analysis, factor analysis, multidimensional scaling, cluster analysis, canonical correlation analysis, discriminant analysis, and latent structure analysis. There are also other intelligent systems methods that use techniques such as neural networks, fuzzy logic, and genetic algorithms. In stochastic methods, Bayesian analysis has been popular as a technique in model building.

When data-mining techniques are applied to a specific area or a specific problem, prior knowledge about the system can simplify the process. Applying theoretical or blind techniques on the data in the hopes of finding some structure can be a daunting task or practically and computationally intractable. In the area of transportation safety, prior knowledge based on practitioner insights and theoretical fundamentals related to transportation, safety, and human behavior should be utilized to perform effective extraction of knowledge from the data. Thus, existing information about the system allows for the derivation of a nominal structure of a model; parameters for the model can be determined by using the data on that structure, as shown in figure 1.
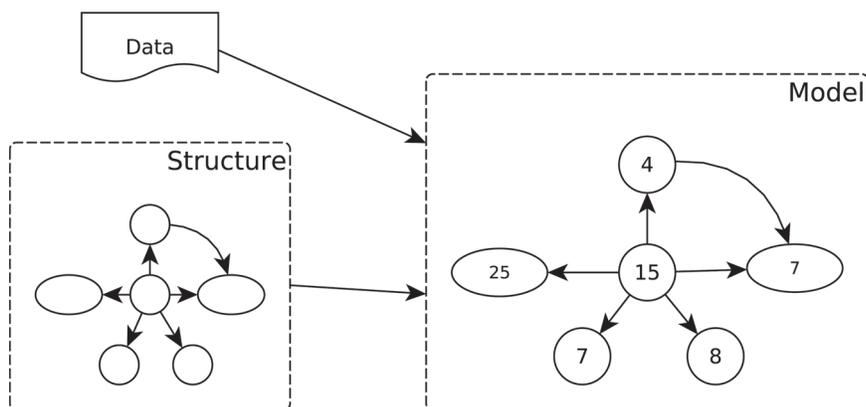

Figure 1 Data Structure Model

Feedback Control for Modeling

Feedback mechanisms have been used to control systems in the history of humankind. As far back as 300 BCE, Greeks and Arabs used feedback mechanism to keep track of time (Lewis 1992). During the industrial revolution, steam engines utilized control mechanisms to operate efficiently. Since then, feedback controllers have been used for machines, vehicles, and multiple types of systems. In fact, adaptive advertisements employ feedback mechanisms to determine which promotions should be displayed to consumers based on their previous click-stream behaviors. For instance, feedback control has been used to improve consumer decision quality (Krishen and Nakamoto 2009), and also handle consumer information overload in choice sets on websites (Kheirandish, Krishen, and Kachroo 2009; Krishen, Raschke, and Kachroo 2011).

A system can be controlled in an open-loop structure where the output of the system is not measured or used to make changes to control actions. However, since it is almost impossible to know the exact model of any system, an open-loop system cannot be expected to perform with a very high accuracy. In feedback control, we use sensors to estimate the state of the system, and the real-time control action uses the measured output to derive the control action to be performed. To design a feedback control law, we only need a nominal model of the system that should be simple, but must include the essential dynamics of the system. In relation to this, Shang, Tjader, and Ding (2004) explore the potential of applying the analytic network process (ANP) to evaluate transportation projects in Ningbo, China. Advantages of using ANP over traditional hierarchical analysis tools include feedback and interdependence among various decision levels and criteria. Shang and colleagues argue that the model incorporates a much wider range of factors, which they classify as benefits, opportunities, costs, and risks; conventional transportation evaluation methods normally lack these elements.

Our methodology of using a structured model—static model (e.g., a structural equation model); a dynamic model (e.g., a Markovian model); or a stochastic hybrid system model (Lesser and Oishi 2014)—can capture the known nominal structure of a static or dynamic system. Modeling with latent variables can make the model much simpler in comparison with using only measured variables if the real system does in fact have the influence of those latent variables. In the context of safety culture, since the system is cyber-physical, human-system interaction and its implication to safety can be captured by models with latent variables. One advantage

of using a nominal model is that it allows for parameter estimation with measured data and therefore more effective model validation. If the model is not appropriate, an iterative modification can be applied, followed by repeating the steps of modeling to derive the new model. These iterations can continue until we obtain a model within a predefined range of acceptability, or until we reach a prespecified upper bound iteration count failing to find a model. This modeling flow chart is shown in figure 2.

The proposed feedback-based transportation traffic safety framework can be implemented in a phased manner, as shown in figure 3. During phase 1, we gathered observational data from 10,343 drivers; the purpose of this collection was to verify a core driver safety issue. In some cases, transportation-related marketing campaigns target distracted drivers for single-infraction offenses such as No Phone Zone (Nevada Department of Transportation 2014a) and Click it or Ticket (Boatman 2014). On the other
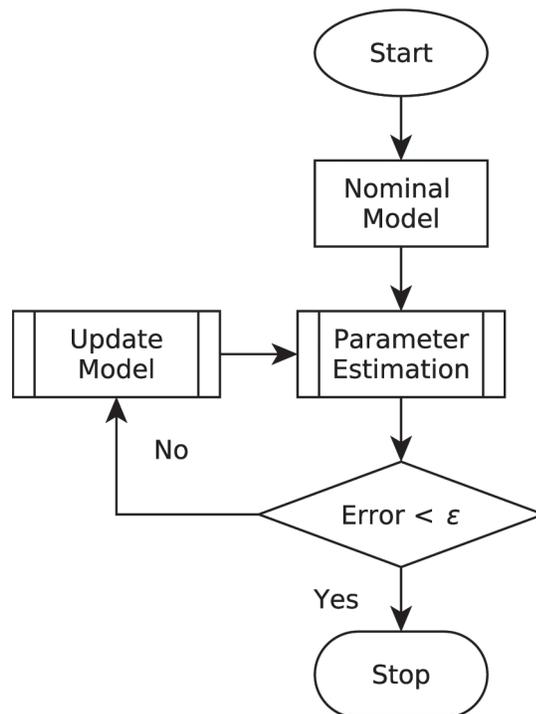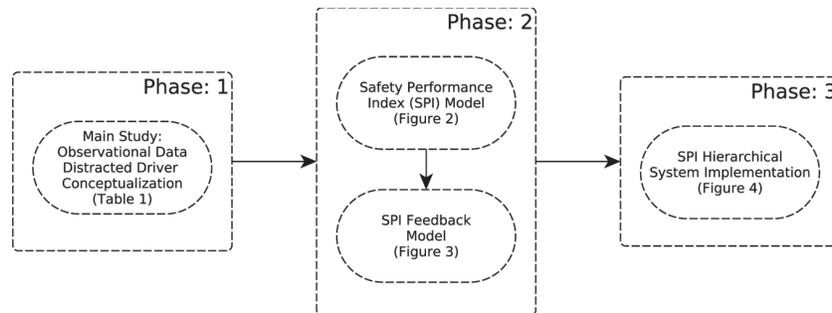

Figure 2 Modeling Flow Chart

Figure 3 Research Methodology

hand, other campaigns are aimed at a combination of multiple unsafe driving practices, for example Bad Driving (Clark County Nevada 2014) and Zero Fatalities (Nevada Department of Transportation 2014b). However, a recent study by Abouk and Adams (2013) finds that drivers change their behaviors temporarily after law enforcement threats are announced but eventually return to their dangerous habitual behaviors. For this reason, the goal of our main study is to verify existing notions regarding distracted driving.

Main Study

Participants and Procedure

This study utilizes observational data collected from various locations in the western region of the United States following a complex sample framework (Sancheti, Kachroo, and Amei 2012). Multiple trained data collectors recorded the following information (based on best approximation): (1) whether or not the driver was wearing a seat belt; (2) number of passengers inside the car; (3) whether or not the driver was using a cell phone while driving; and (4) any demographic information such as age and gender (approximated). A total of 10,343 observations of cars in southern Nevada were collected for the dataset.

Results—Main Study

The pertinent data are given in table 1, which consists of the frequency and percentages for the number of drivers wearing seat belts and whether they were or were not using cell phones during the observation frame.

Of particular interest are the drivers with and without seat belts who are using cell phones. The ones who were wearing their seat belts and using

Table 1/Main Study Results

Observation			Fre-quency	Percent	Valid Percent	Cumu-lative Percent
Driver wearing belt	Valid	Driver not using a cell phone	9,491	98.4%	98.4%	98.4%
		Driver using a cell phone	158	1.6%	1.6%	100.0%
		Total	9,649	100.0%	100.0%	
Driver not wear-ing belt	Valid	Driver not using a cell phone	648	97.2%	97.2%	97.2%
		Driver using a cell phone	19	2.8%	2.8%	100.0%
		Total	667	100.0%	100.0%	
Don't know	Valid	Driver not using a cell phone	27	100.0%	100.0%	100.0%

a cell phone consisted of 158 out of 9,649 (1.6%) and the ones who were not wearing their seat belts and using their cell phones consisted of 19 out of 667 (2.8%). The question we ask about these data is: knowing that the total number of drivers wearing belts was 9,649 and those not wearing belts was 667, is there a significant difference when comparing 158 belted drivers who used phones and 19 unbelted drivers who used cell phones in the second case? In order to calculate this, a Fisher's exact test can be performed (see http://www.langsrud.com/fisher.htm), which essentially is used to examine the significance of the association (contingency) between the two kinds of classification (see http://www.physics.csbsju.edu/stats/exact.html). To determine the probability that there is a correlation between cell-phone usage and seat-belt usage, application of Fisher's exact test shows that the proportion of drivers using cell phones without seat belts is significantly higher than those using cell phones with seat belts ($p = 0.03$).

Thus, this observational study shows that those who are unsafe in terms of seat-belt usage are more likely to be unsafe in terms of cell-phone usage as well. Whereas this is a not a causal relationship, the correlation does appear to be significant. This finding warrants a framework to define a traffic safety indicator that is derived from multiple data sources.

Proposed Hierarchical Feedback-based Transportation Traffic Safety Framework

Interdisciplinary systems must be designed that can create adaptive safety communications, determine appropriate monetary levels for various transportation issues, and employ safety mechanisms to improve the overall safety culture in various geographic locations. Of utmost importance is the ability to take data, which exists in abundance, and overlay a feedback

control model around it to improve safety performance. As shown in figure 4, phase 2 begins by identifying a framework in which multiple data sources should be synergized to create a safety performance index (SPI) in a feedback model design. Next, the feedback model for the safety performance index will derive the important latent variables for a structural equation model of salient safety constructs (see figure 5). Finally, the model can be systematically implemented by targeted communications to increase performance measures at various stages to increase traffic safety, as in figure 6.

Our conceptualization begins with figure 4, which depicts the basic feedback control loop–based structure of our framework. The figure shows the flow of data that is obtained from various data sources and sensors. That data is then processed in software and performance measures are estimated using the appropriate mathematical formulation. These measures are then fed into the model of the system from which the latent safety
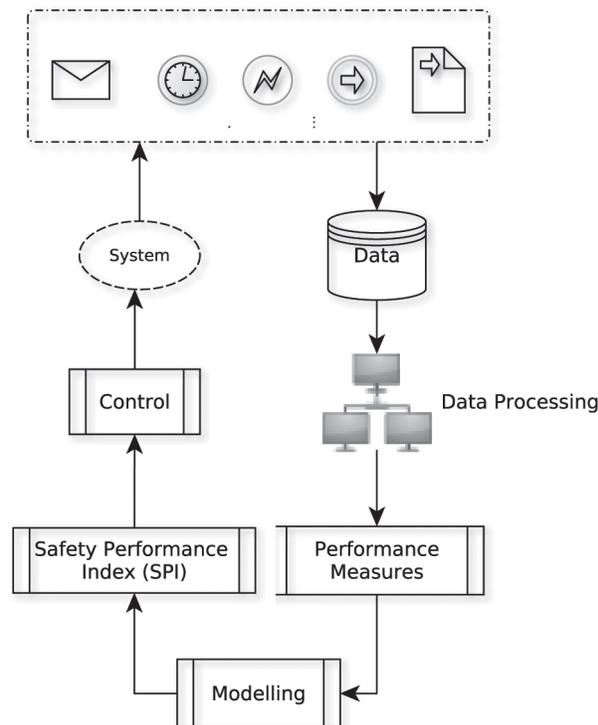

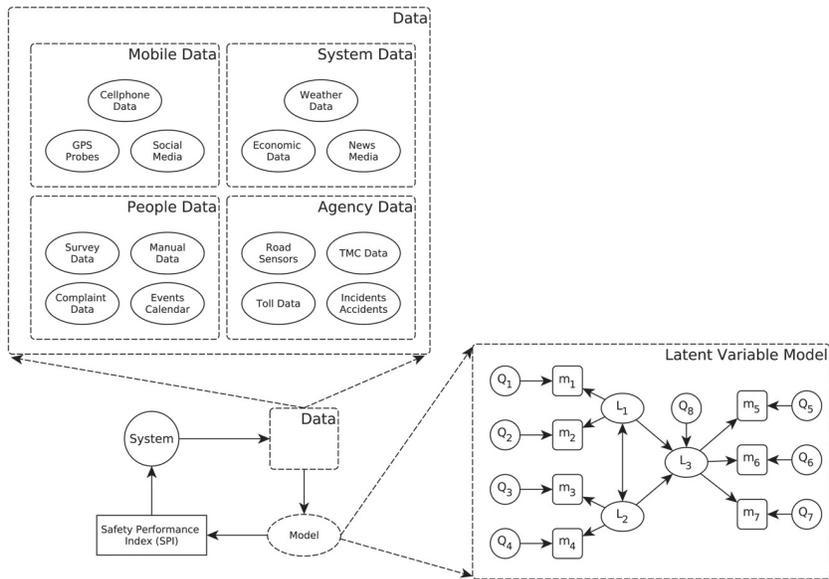**Figure 4** Safety Performance Index (SPI) Model (Phase 2)

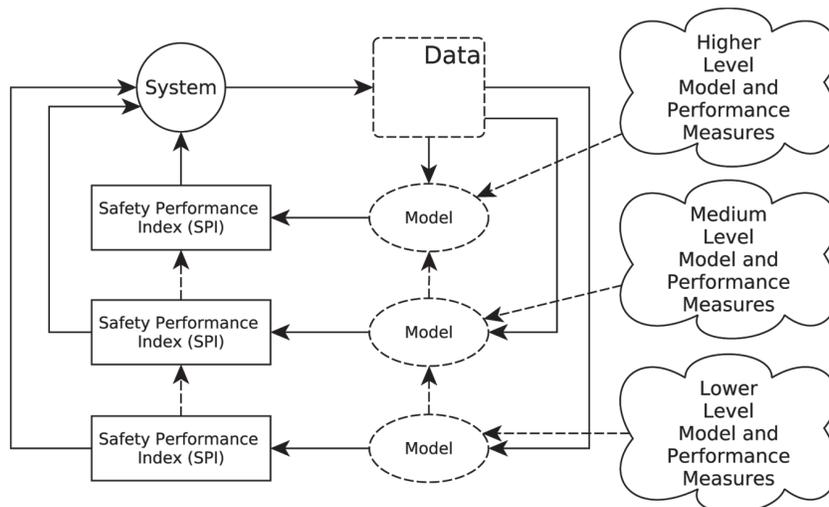**Figure 5** SPI Feedback (Phase 2)

Figure 6 SPI Hierarchical System Implementation (Phase 3)

performance index is computed. Following this, the index can be used to perform the appropriate control action for the system. Figure 5 augments figure 4 by providing more details of the data sources and the model. To further define the available sources, the data have been divided into multiple possible inputs; these include mobile data, system data, people data, and agency data. Mobile data can be obtained from many sources, for example, the data from GPS enabled smartphones, or from cellular network data. Additionally, it can come from transportation-related social media apps, or GPS probes such as the ones used in transit vehicles. The system data provide information about the overall system such as weather data, economic data, relevant transportation news, and so on. People data are the data that involve people activities, including survey data, complaint data, manual data, or data from special events. Finally, there are data that are collected by transportation agencies, such as that obtained from road sensors, Traffic Management Center (TMC) data, toll data, and data related to incidents.

The most important part of our framework is the modeling to capture the safety culture related latent variables of the system. This conceptualization is illustrated in figure 5 as an expansion of the model. In the sample model depicted in the right-hand side of the figure, measured variables, their error sources, and latent variables are all shown. Moreover, relationships between all of the variables are hypothesized in the model. The data collected from the system drives the values of these variables which are then used to compute the system performance index (SPI).

Our overall proposed model is a hierarchical framework that works at various levels (see figure 6). As an example, safety is important at a signalized intersection where pedestrians and vehicles are involved. The data for this can come from sources including traffic sensors, complaint systems, traffic reports, and survey data. Based on all of the data sources as inputs, a safety model can be derived that will define latent variables and their relationships, and then use those to provide action or control. There are many control actions that are relevant to this example. For instance, the programming of the signal timing can be changed, more sensors can be added at the site, or flashing lights can be installed at the location. At a higher level, we could be interested in controlling all of the intersections and midsections of the road, which would include the signalized intersection of the previous example. Thus, the safety index of the entire road depends on the safety indices of each of its components. A higher level of modeling could involve an even larger network. The total data for the system has measurements that could be relevant to one or more of these levels. The SPI values

at a lower level are fed into higher levels to achieve consistent modeling and a hierarchical computation structure. The control actions at various levels can also be different. In particular, at the highest level in a system state, the control action could be a policy decision regarding safety, such as to pass a law banning texting while driving, or it could be a budget allocation problem for various projects.

Conclusions and Future Research

Our framework is designed to handle the complexities inherent in complex systems with a phased approach. We contribute to existing theory on safety culture by providing a feedback mechanism by which to structure the systematic problem of safety. The most important aspect of our model is the interdisciplinary nature of our overall safety culture solution. In effect, by including data from nontraditional sources (e.g. social networks, blogging sites, product commentaries) in our model and utilizing existing qualitative techniques to analyze the data (Krishen et al. 2014) while also including quantitative data with quantitative techniques, we can maximize the conceptualization of safety culture. Our model aims to transcend traditional communication mechanisms between transportation and marketing, such that big data can better inform marketing communications. We therefore propose the following future research based on our model:

1. Safety Culture Conceptualized as a Subculture, Community, or Tribe

Several concepts regarding groups of individuals, including virtual communities, subcultures of consumption, and consumer tribes, share a theoretical underpinning regarding the meaning of membership within them. For example, for virtual communities, Healy and McDonagh (2013) discuss seven consumer roles, such as voice, loyalty, exit, entry, and twist, all of which are represented by various consumer actors. Whereas loyalty as a role involves attachment to the community or brand, twist entails the use of a product, symbol, or service in a way that was not originally intended by the firm. In its original definition, a subculture of consumption is a subgroup of individuals who voluntarily participate as members, sharing activities, beliefs, and values (Schouten and McAlexander 1995). Cova and Cova (2002) describe consumer tribes as a network of heterogeneous individuals, linked by shared passion, and able to create collective action and advocacy. Whereas some of these conceptualizations, such as subcultures and communities, identify individuals as a homogeneous group;

others like tribes include heterogeneous consumers acting as a collective. Recent research highlights the nature of a running community or subculture, postulating that heterogeneity, belonging, and tension characterize membership (Thomas, Price, and Schau 2013). Following the conceptualizations of groups of networked individuals forming shared memberships and collective action, Krishen et al. (2014) describe two political tribes based on collective good and self-interested actors, within the domain of transportation taxation communication. Similar to subcultures, communities, and tribes, the formation of a safety culture will require shared values and ethos, tension while negotiating group boundaries, and a sense of belonging, in order to enable collective action.

2. Qualitative Data to Quantitative Model

This mechanism proposes the use of data in natural language, such as a complaint system where people's complaints have been recorded. Such data can be processed using natural language-processing techniques and then models based on elements including sentiment analysis can be obtained. These models have quantitative information derived from processing qualitative language data. These models can be then used in conjunction with models built out of quantitative data, or ways to synthesize qualitative and quantitative data can also be developed.

3. Qualitative Research Methods for Building Nominal Quantitative Models

Qualitative research methods normally involve ethnographic studies that involve deep qualitative analysis of a very small sample size as compared to statistical methods that require quantitative data of a much larger sample size. These techniques can provide a starting point for building the nominal model for the quantitative model-building in our framework. Qualitative data from interviews and surveys can be used to derive variables and nominal relationships among them before quantitative data can be used to obtain parameters of that model in the iterative process of model improvement. For a complex system we can use the Fuzzy Set Qualitative Comparative Analysis (fsQCA) method to combine the qualitative knowledge from different parts of a complex system (Ragin 2008; Wu, Yeh, and Woodside 2014). In order to extract more out of the qualitative data, the fsQCA methodology can be employed, the outcome of which can be used as the starting nominal model for the quantitative model building with latent variables such as the structural equation models for static modeling or hybrid stochastic models for the modeling of dynamic phenomenon.

Note

The first three authors contributed equally in the preparation of this manuscript.

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