Building Low-Error Public Transportation Systems

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Abstract: High Reliability Organizational (HRO) research suggest that some organizations and systems are that routinely conduct complex operations with little or no error share certain characteristics. A 76-year longitudinal case study of the evolution of error-intolerance of the FAA’s air traffic control services produced a set of specific structural and behavioral actions that, if implemented, promise to achieve high reliability and safe operations within transportation systems. A conceptual systems model has been constructed to demonstrate how legislative oversight, agency regulatory programs, and industry processes combine into a highly redundant and effective operational structure. A scale has been created for measuring and improving performance at the policy and agency levels of government and at operational transportation levels. It is proposed that adoption of this model will deliver quantifiable improvement in both service provision and safety of public and private transportation networks.

Governmental organizations responsible for ensuring the public’s safety and security are expected to perform critical and often complex missions that are vital to the welfare of Americans. How efficiently government agencies perform their missions has real consequences for all citizens. However, while many public agencies regularly deal with critical issues affecting citizen safety and security, their ability to provide crucial services reliably varies between agencies and programs. Error appears to be far more common and tolerated for organizations tasked with reducing career criminal recidivism, drug use, or drug trafficking than for organizations tasked with operating air traffic control (ATC), nuclear power, or military nuclear weapons systems (Frederickson and LaPorte, 2002; Hargrove and Glidewell, 1990). Interestingly, tolerable error within transportation modes appears to be variable as well. Highway fatalities for the United States from 1994 through 2007 averaged over 42,000 deaths (NTHSA, 2008) compared the 72 deaths per year average experienced by commercial aviation (NTSB, 2008). The near collapse of the American financial industry serves as another contemporary example of what can happen when governmental regulatory oversight agencies are too error-tolerant. Importantly, there are existing models of regulatory and oversight systems that operate reliability, with high levels of productivity and extremely low levels of error. The study of one of these systems produced a model that can be used to improve the performance of failing or low performing regulatory and service agencies.

In the mid 1980s, a research group from the University of California at Berkeley began investigations to identify the processes that enabled organizations like the Federal Aviation Administration’s (FAA) ATC, nuclear power plants, and the United States Navy’s aircraft carriers to operate with high degrees of mission reliability while experiencing exceptionally low error rates (Laporte, 1996; Laporte & Consolini, 1991; Roberts, 1990a; Roberts, 2001; Sagan, 1993; Weick & Roberts, 1993). Building on this pioneering research, an investigation was conducted (O’Neil, 2008) that assembled a scale capable of evaluating policy and agency-level error-intolerance (EI) in organizations. This investigation also produced a practical model that can be employed to decrease error within public agencies and for the critical programs that these agencies regulate. Use of EI scaling and the EI model provides a framework that decision-makers can use to significantly reduce error while significantly improving safety and operational efficiency within transportation systems.

Background: Using a "behavioral observational approach" (Roberts, 2001, p. 10943), the Berkeley interdisciplinary research group conducted a series of investigations that identified the characteristics and descriptive attributes of highly reliable and error-intolerant, high-reliability organizations (HROs), attributes and characteristics that differentiated them from more error tolerant organizations like those dealing with criminal recidivism and drug trafficking (Creed, Stout & Roberts, 1993; Frederickson & LaPorte, 2002; Hirschhorn, 1993; Koch, 1993; LaPorte, 1988, 1996; LaPorte & Consolini, 1991; LaPorte & Rochlin, 1994; LaPorte & Thomas, 1995; Roberts, 1989, 1990a, 1990b, 1993, 2001; Roberts & Brea, 2001; Rochlin, 1993, 1996; Rochlin, LaPorte & Roberts, 1987; Rochlin & von Meier, 1994; Schulman, 1993; Weick, 1987; Weick & Roberts, 1993). Together, this body of work produced a range of descriptive attributes associated with HROs. However, HRO research did not group these attributes into a scaling to evaluate or differentiate error-intolerance in organizations, nor did this pioneering research provide any detailed information as to how these exceptionally performing organizations were formed. O'Neil (2008) conducted a 76-year longitudinal case study of the evolution of the American air traffic control system. As part of this effort, EI attributes and associated operational characteristics were identified and refined from the HRO literature into a rudimentary scale capable of evaluating error-intolerance at both policy- and agency-levels of government. This project also produced a model that can be used to measure and improve performance at policy- and agency-levels of government.

II. The Emergence of High Reliability-Low Error Organizations

Many scholars and public officials have accepted as inevitable that people performing their jobs will make mistakes and that machinery will break down. Because of personal- and technologically- based error, it is assumed that no organization will ever perform perfectly and, as a result, bureaucracies are not expected to be "error-free" (La Porte & Consolini, 1991, p. 19). However, Berkeley researchers identified several complex technical organizations that perform critical public services without failure (Rochlin, La Porte & Roberts, 1987, p. 1). These organizations were identified as successfully initiating strategies designed to eliminate "organizational predilections" contributing to error that reduced the organization's mission reliability (Roberts, 2001, p. 10942). Interestingly, unlike many traditional risk mitigation theorists who tended to focus their study on organizations that suffered accidents, the Berkley group focused on organizations with remarkable operational safety records whose apparent "devotion to zero error" was accompanied by very high levels of mission task reliability (Rochlin, La Porte & Roberts, 1987, p. 1).

Definition of Error and Error-Intolerance. Reason (2000) states that error can be viewed as the product of individuals or of systems. Individual error, the "person approach," views error as the outcome of an unsafe act or a procedural violation on the part of an individual (p. 768). The person approach blames the individual for the error, citing "forgetfulness, inattention, or moral weakness" (p. 768). The "systems approach" views error as the failure of an organization to acknowledge that humans are fallible and prone to error. Under the systems approach, error reduction focuses on the working environment and constructs safeguards or "[defences] to avert errors or mitigate their effects" (p. 768). The person approach to error is the most prevalent because it is easier for managers and organizations to place blame error on the actions of individuals than on institutions. Under the person approach, corrective action is considered complete once following admonishment, retraining, or firing of the person(s) deemed responsible for causing the error. The person approach, while more likely to be used, is not effective in controlling error and seldom makes organizations safer. Reason contends that error-intolerant organizations view human error as a systems problem and institutes system solutions to control error (p. 770). This systems approach is the key to error mitigation in the EI model.

La Porte and Consolini (1993) defined error as a "mistake or omission in procedure or operational decisions that result in occurrences judged as undesirable and sometimes costly to remedy" (p. 23). Errors of sufficient magnitude that threaten organizational viability, either in part or whole, are considered system failures (p. 23). Error is frequently associated with unexpected and undesired events. All organizations are expected to experience some magnitude of error. Some error is costly to remedy. Some error may be considered catastrophic, having dire consequences for the people the organization serves and threatening the viability of the organization itself. However, EI organizations demonstrate the ability to conduct operations using high-hazard technology through limiting and containing error and controlling risk. Subsequently, an error-intolerant organization can be defined as one that performs its mission by managing a nearly error-free "high-hazard/low-risk system" that employs dangerous technology while virtually never experiencing "an operating failure of grievous consequence" (La Porte & Consolini, 1991, p. 23)[1]. It was by this definition that the FAA's air traffic control (ATC) function, nuclear power production, and the Navy's operation of aircraft carriers were defined as error-intolerant programs (Frederickson & La Porte, 2002; La Porte & Consolini, 1991; La Porte, 1996; Roberts, 1989, 1990a; 2001; Rochlin, La Porte & Roberts, 1987).

A key system characteristic differentiating error-intolerant organizations from other groups is their dependence on redundancy. Redundant systems consisting of both technology and operational protocols are utilized to prevent error (Frederickson & La Porte, 2002; La Porte, 1996, Laporte & Consolini, 1991, Perrow, 1999a; Rochlin, La Porte & Roberts, 1987; Roberts, 1990a, 1990b, 1993, 2001; Roberts & Bea, 2001; Sagan, 1993). Redundancy reduces the probability of consequential failure and minimizes the loss of performance enhancing information. Using centralized/decentralized decision-making strategies also reduces organizational error. The centralized part of this process is responsible for setting and instilling clear "operational goals and assumptions," while the decentralizing part grants decision-making authority to low-level personnel closest to the problem (Rijpma, 1997, p. 17). This centralized/decentralized strategy of decision-making enables the organization to identify and mitigate potential error occurring in tightly coupled systems at the point of origin, before it can escalate and cause system failure. Error-intolerant organizations become learning entities as information flows from peripheral operations into the center and back again through a redundant

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[1] Error-intolerance and High-reliability are considered almost interchangeable for the purposes of this study. However, it is conceivable that organizations can be actively seeking to achieve error-intolerance, but not be operationally reliable. Consider NASA's current shuttle program. While striving to reduce organizational error, it frequently cancels launches due to weather, mechanical and other issues. While it is striving to be error-intolerant by not launching, because it frequently cannot launch it is not operationally reliable.

information network. Costly events motivate substantial operational improvements. Lessons learned through real-time are identified and incorporated into the organizational knowledge base and are supplemented by formal training and use of simulation to reduce error and improve operational standards (Rijpma, 1997).

Of particular note, although trial-and-error learning is important for HROs, trial-and-error operations are not. Failure of critical technologies like nuclear power and air traffic control are viewed by both operators and the public as unacceptable (La Porte & Consolini, 1991, p. 19). Thus, mistakes commonly arising from trial-and-error operations are not acceptable. Subsequently, HROs seek “trials without error, lest the next error be the last trial” (pp. 19-20). As a consequence, unlike other organizations, failure-free operations become the standard for HROs (La Porte & Consolini, 1991, p. 20).

Challenges to Error-intolerant, High Reliability Organizational Theory

There are two theoretical challenges to error-intolerant HRO theory. The first is a general theoretical challenge of any HRO’s ability to prevent error. The goal of eliminating error is viewed as opposing not complementing Normal Accident Theory (NAT). The second challenge category contains specific criticisms of key elements or actions critical to the characterization of error-intolerant organization operations.

Charles Perrow (1999a) and Scott Sagan (1993) question the feasibility of error-intolerant organizations to prevent catastrophic events in tightly coupled and complex organizations that use hazardous technology. In tightly coupled systems there is no buffer or slack between mechanical components. The operation of one component directly affects the operation of other mechanical components (Perrow, 1984, p. 90). The basis of the NAT argument lies in the use of redundant, tightly coupled, and interdependent safety protocols to control error. It is contended that these redundant interfaces increase complexity and therefore produce unforeseen interdependencies that not only contribute to error but also may actually cause it. Sagan (1994), though not advocating “abandonment of dangerous technologies simply because they are dangerous,” states that it is delusional to believe that “such complex and tightly coupled systems can be made perfectly safe” predicting that even “well-managed operations” will experience accidents (p. 238).

Both Perrow (1999b) and Sagan (1993; 1994) view NAT as the opposite of HRO theory. Perrow (1994) argued that it was valuable to contrast the two theories as opposites. Perrow criticizes the HRO research as being limited to only a few outlier organizations that were not tightly coupled and did experience very few failures. He indicated that the value of researching those organizations was limited because inquiries did not provide sufficient examples of organizations that did fail. HRO theorists (LaPorte and Rochlin, 1994, p. 222) replied that there was already ample literature dealing with error prone organizations, but a dearth of studies examining organizations that operated with exceptionally low levels of error. Importantly, LaPorte (1994) and LaPorte and Rochlin (1994) assert that it was the study of these unique organizations that resulted in their belief that NAT and HRO theory are in fact complimentary. HRO theorists do agree that organizational error is inevitable but have identified the existence of strategies that appear to limit both error and the magnitude of organizational failure resulting from error.

HROs have not experienced the failure predicted by NAT theorists. HROs continue to manage complex, tightly-coupled systems, relying on protocols and checklists, and using centralized/decentralized decision-making schemes to avoid major error. The operational failures predicted to occur within critical and dangerous industries like the nuclear power industry have not taken place. FAA air traffic control centers (ATCCs) and U.S. Navy's aircraft carriers continue to routinely conduct "nearly error-free" operations (Roberts, 1990a, pp. 101-102). Though "sustained failure-free performance is, from a theoretical view, quite extraordinary," it is being achieved by organizations using HRO practices (Laporte and Consolini, 1991, p. 20).

Four policy-level attributes government connection, external oversight structure, resource allocation, and safety prioritization and their associated identifying characteristics (Table 1) can be used to evaluate and assess policy maker error-intolerance (O'Neil, 2008).

Table 1 Policy-Level Attributes and Characteristics of Error-Intolerance

Policy-Level Attributes	Characteristics Associated with Error-intolerance
Government Connection	Type of Reporting relationship of senior policy-makers and other senior governmental agencies to regulatory agency(s). None No organizational status. a. Regulation by federal government to control error b. Exists as independent organization or is considered major component of Department possessing substantial regulatory authority c. Senior regulatory agency officials report directly to Executive and Legislative branches
External Oversight Structure	Senior policy-makers seek and maintain strong regulatory authority over agency. Build system of overlapping and redundant organizations to monitor and assist in oversight of agency/organization. None No oversight committees or boards used by Executive, Legislative or Judicial Branches a. Use of traditional executive branch, congressionally appointed or standing sub committees; judicial, or designated governmental groups to exercise oversight of regulatory agency b. Use of dedicated and independent specialized oversight bodies external to regulatory agency c. Use of periodic externally directed audits/inspections to evaluate and monitor aviation regulatory agencies and produce recommended actions to decrease error.
Resource Allocation	Levels of funding tend to be high None Funding does not support agency tasking a. Funding is adequate to meet agency operational requirements. b. Funding supports expansion of agency mission & operation c. Finding is increased specifically for safety and error prevention.
Safety Prioritization	Decision-making evidence reveals that concerns for safety result in establishment of multiple and redundant specialized safety programs and systems to reduce error None Absence of safety programs or reliability measurement programs. a. Use of safety/reliability measurement programs in process improvement initiatives. b. Actions taken to identify, reduce or eliminate precursors associated with causing or contributing to potential error (accidents or failures). c. Use of redundant and overlapping specialized safety programs or agencies to target and reduce error

Eight error-intolerance attributes (Regulatory Structure, Training, Formal System Improvement, Specialized Personnel Requirements, Communication/decision process, Safety Prioritization, Technical Competency Standards, and Funding) were also derived from the HRO literature (Table 2) and used to evaluate internal structural and behavioral change within the FAA itself or in a preceding agency, in response to policy change.

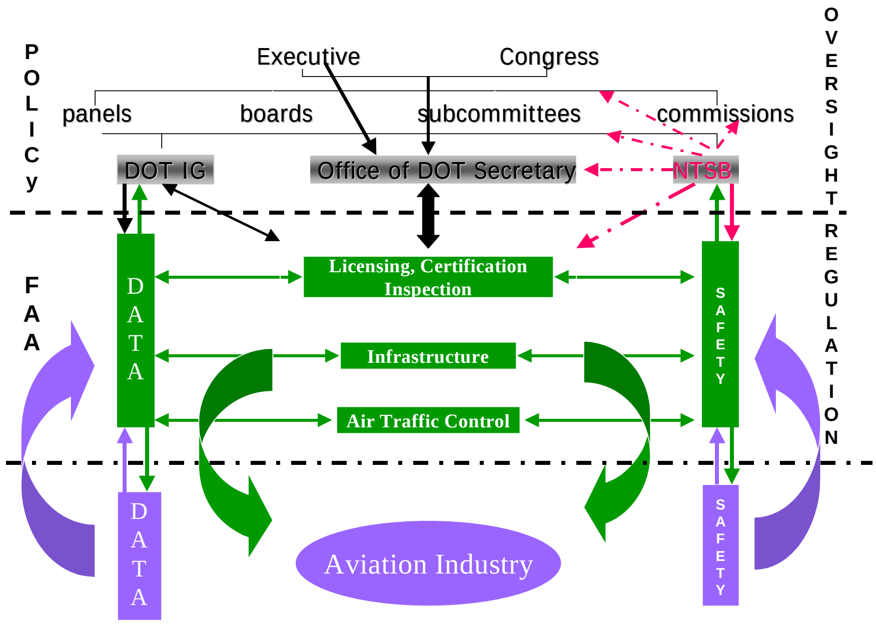
Table 2: Agency-Level Attributes and Characteristics of Error-Intolerance

Attribute	Characteristics Associated with Error-intolerance
Regulatory Structure	Clearly defined centralized organizational structure for control of agency and regulated industry None No or weak regulatory control of agency and industry a. Centralized authority exercising control over agency b. Expands regulatory control in areas affecting agency performance and authority c. Establishes uniform and standardized external and internal rules to guide agency operations d. Establishes clear lines of organizational authority and employs formal reporting structures and procedures e. Formal systems of information sharing (communication streams) employing regular information distribution system (newsletters, professional publications, etc)
Training	Rigid and Demanding Standardized Training structure for organizational members. None Little or formal training; trial-and-error training on-the-job dominates a. Standardized training by centralized training facilities or syllabus is required for new personnel 1. Pass or fail criterion used 2. Dismissal of personnel with substandard performance b. Reoccurring training required for experienced personnel. c. Training integral for professional advancement.
Formal System Improvement	Development and institutionalization of Safety Programs for internal and external operations improvement None No evidence of formal system improvement programs targeting error reduction a. Establishment of operational/safety reporting programs within organizational structure for error reduction & elimination b. System of permanent and special inspections to identify and prevent error c. Redundant mechanisms designed to collect and analyze safety information and reliability data to reduce error and improve organizational performance d. Presence of formal reward and incentives programs targeting identification of potential error -Protection for reportees -Incentives for identification of safety problems -Incentives for reporting best practices or improvements e. Mechanisms for distribution and notification of safety and system improvement
Specialized Personnel Requirements	Specified organization requirement for specialized and technically educated personnel None No specialized personnel required to perform organizational tasks a. Specialization education, skills or aptitude required to work in organization b. Potential personnel are subjected to rigid screening and selection criteria c. Personnel are well compensated for specialized talents and training d. Specialized personnel are supervised by specialized supervisors -Supervisors are normally qualified within same specialized area e. Specialized personnel represented by specialized organizations (trade groups, unions, etc)
Communication/Decision Process	Organization constructs formal and operational system of decentralized-centralized decision-making None Hierarchical organization decision-making, all decisions emanating from top-down. a. Policy formed centrally, but operational decision making is distributed b. Mid level-managers have autonomy and display flexible decision-making in high-tempo operations within area of responsibilities. c. Local area managers have discretionary and independent decision-making powers for operation d. Communication and information sharing is conducted in timely manner up, down, and laterally within the organization -Emphasis on lessons learned, error prevention ideas, and practices -Regular "newsletter" information sharing mechanisms e. Emergency system of communication exists throughout organization to disseminate critical information and aid in operational decision-making

Safety Prioritization	Safety is the highest priority None Safety is considered secondary to economic considerations a) Safety is considered of equal importance to economic considerations b) Safety during operations is priority over economic considerations -Operations is halted or interrupted for safety c) Emerging technology developed and employed for error reduction d) Creation of redundant and overlapping systems to reduce error. e) Specialized and redundant systems of safety information gathering reporting, error submission, and information sharing exists
Technical Competence Standards	Maintain high levels of technical standards expertise. None No technical standards established for jobs. a. Certification process required for personnel to demonstrate technical competence b. Recertification process required for experienced personnel to ensure continued competency c. Development of technical competence in new personnel -Placed in less stressful and demanding environments until experience acquired. -Operators heavily monitored when first exposed to actual job -Often tied to primary training supervisor -Systematically monitored, evaluated by trainers/supervisors d. Initial qualification and ongoing recertification dependent on simulation and role-play. -Simulations and exercises routinely performed. -Exercises are routinely conducted to simulate situations that may cause error or failure, in order to train operators in early identification and prevention e. Workers moved progressively to more demanding positions or responsibilities as experience is acquired and satisfactory technical competence is displayed.
Funding	Systems do not suffer from funding shortfalls None Funding does not support organizational mission or ability to control error. a. Budget allocation distribution supports organizational mission b. Internal organizational error or failure results in reallocation of funds to agency areas programs associated with error/failure c. Identified areas of potential error or failure receive increased funding and resource.

The Federal Aviation Regulatory System Model: During the study of the evolution of error-intolerance in America's air traffic control system, a model of oversight and operation was discovered (Figure 1) that demonstrates the operation of a fully mature policy-agency-industry EI system. Level 1 of the model is policy and oversight, level 2 is FAA regulations and operations, and level 3 is aviation industry management and operations. The policy-oversight level of this error-intolerant system contains a specialized and redundant oversight structure beyond aviation policy-making. In addition to traditional executive and legislative commissions, panels, boards, and subcommittees, aviation oversight employs three dedicated and specialized bodies to monitor and direct FAA operations. While overlapping in many areas, the Office of the DOT Secretary, the DOT Inspector General Office (IG), and the NTSB independently perform specialized and critical oversight functions.

Figure 1: The Federal Aviation Regulatory System



The Office of the DOT Secretary serves as a direct and authoritative link to the Office of the President and, when necessary, can exercise direct control over FAA operations to mitigate agency error and improve the agency's aviation safety regulatory programs. The independent DOT IG routinely conducts audits and evaluations of internal FAA programs to assess the agency's compliance with executive and legislative directives and ensure that the FAA complies with its own rules and procedures. The IG also regularly evaluates aviation industry programs to ensure compliance with federal regulations and directives. As a separate agency outside of the DOT, the NTSB independently monitors, collects, and analyzes performance data from both the aviation industry and FAA operations. The NTSB is politically and administratively insulated so that it can promulgate unbiased recommendations to improve aviation safety. Thus the policy oversight portion of the aviation regulatory model provides a complex, redundant, and resilient system of oversight that continuously gathers, evaluates, and distributes information with the expressed goal of reducing FAA and aviation error.

The FAA regulation level of the system model (Figure 1) uses a redundant internal regulatory strategy that incrementally evolved to identify, control, and mitigate error in the aviation industry. Since 1926, when aviation safety regulation began with the Air Commerce Act, the agency has utilized a three-prong operational safety strategy (Table 3) consisting of aviation industry regulation, the management of aviation infrastructure and operations (airways, navaids and airports), and air traffic management. Throughout five legislative eras encompassing over eighty years, these regulatory and management functions continued to interact while incrementally evolving and expanding in scope and influence.

Table 3: Agency-level Safety Strategy

Safety Strategy	Agency-level Function*	
1- Industry Regulation & Enforcement	Licensing of aircraft. Inspection of aircraft. Supervision of aircraft marking. Licensing of pilots and mechanics. Rating of flying schools. Certification of private aeronautic radio Enforcement of regulations	**Analysis of accident statistics** **Dissemination of Information**
2- Infrastructure Management	Installation and maintenance of airways Distribution of information regarding flying conditions. Ratings of airports	
3- Air Traffic Management	Making air traffic rules.	

*See Schmeckebier, 1930, p. 21, for detailed description of Aeronautics branch functions under the Air Commerce Act

The ability of the FAA's air traffic management section to control thousands of commercial aircraft per day with virtually no safety error is an outcome stemming from the complete integration and interdependence of all three parts. For example, although air traffic control (ATC) is an FAA function that falls under Safety Strategy Part 3, Air Traffic Management, ATC does not function independently. Licensing, certification, and inspection functions ensure that only specialized and certified personnel operate and maintain aircraft. Over many years redundant safety systems, both technological and procedural, have been mandated and incorporated into aircraft and flight operations to increase ground and airborne operational safety. Within this part of safety strategy, the FAA and its predecessors used various routine and specialized inspections and audits to ensure that these safety systems were not only maintained, but also improved.

In the infrastructure portion (Part 2) of the safety strategy, the FAA operates, maintains, and oversees a complex system of navigation aids, approach technologies, and airport facilities to provide highly standardized and safe aviation operations. The FAA's highly specialized and standardized system of air traffic control (Part 3) utilizes redundant technologies and procedural protocols to ensure safe separation of aircraft in the air and on the ground. Importantly, these three internal strategies interconnect technology, information, and procedures to form an interdependent system whose functioning is responsible for safe operations. Each strategy supports the other, and FAA operations, especially airborne, are dependent on the proper functioning and interaction of all three regulatory strategies. As a consequence, the development of error-intolerance within both the FAA and its ATC services is due to the federal aviation regulatory structure evolving as part of a larger error-intolerant system (Figure 1).

In the industry level of the Federal Aviation Regulatory System Model (Figure 1), it was observed that some degree of regulatory capture of the aviation industry by the FAA had occurred, where aviation industry groups themselves began to employ error reduction strategies and programs associated with error-intolerant systems. The aviation industry initiated its own independent data collection and information dissemination network to reduce maintenance and operational error.

It is important to note that the key characteristics identified by HRO researchers as existing in error-intolerant organizations are present and operating within the Federal Aviation Regulatory System. HRO characteristics observed included program and technological redundancy, use of specialized personnel, internal overlap, use and reliance on safety/reliability measurement programs, and structural resiliency (Frederickson & La Porte, 2002; La Porte, 1996, Laporte & Consolini, 1991, Perrow, 1999a; Roberts, 1990a, 1990b, 1993, 2001; Roberts & Bea, 2001; Rochlin, La Porte & Roberts, 1987; Sagan, 1993). These characteristics are employed not only within each level of the federal aviation regulatory system, but between the levels as well. The external functioning and overlap of these characteristics enabled the federal aviation regulatory system to achieve error-intolerance. Findings suggest that error-intolerant organizations are not likely to form on their own in isolation, but will evolve as part of a larger more formal error-intolerant structural system.

Information Flow: The federal aviation regulatory system is critically dependent on the vertical and horizontal flow of information both to achieve and to sustain error-intolerance. While any regulatory oversight program is dependent on information, what makes error-intolerant systems different is the number of formal information-gathering programs that have been initiated and used to gather and share data. FAA policy-makers and the FAA itself are supported by the FAA, NTSB, DOT IG, GAO, and by industry groups that gather and disseminate critical information among all segments within the aviation environment. This redundancy of information gathering and analysis has created a transparent system with access to comprehensive aviation safety data that enables any number of oversight bodies to respond to perceived threats to safety, even threats posed by internally occurring error. As discussed in the literature review, error-intolerant organizations are not error free (LaPorte, 1994; Roberts, 2001). This observation means that the FAA is no exception. However, because the FAA is a component of a larger error-intolerant system, oversight agencies actively seek to identify and mitigate errors within the FAA before they can escalate into a major accident.

In the federal aviation regulatory system, the free flow of operational information enables oversight groups such as the DOT Secretary, DOT IG, and NTSB to detect internal errors on the part of the FAA and take corrective action. For example, in March 1984, in response to information regarding ongoing airline maintenance practice irregularities, the DOT Secretary directed the FAA to initiate a National Air Transportation Inspection (NATI) of major commercial carriers and commuter airlines and a Safety Activity Functional Evaluation (SAFE) of the FAA (Preston, 1998, p. 198). NATI resulted in sixteen airlines receiving fines and losing certification due to their regulatory non-compliance. Project SAFE resulted in the revamping of internal FAA inspection rules and practices so the agency could achieve earlier error detection within the aviation industry and increase the use of the automated Aviation Safety Analysis System (ASAS), designed specifically to provide earlier analytic detection of error (Preston, 1998, pp. 198-199). This is an example of how transparency and visibility of redundant information sources within the Federal Aviation Regulatory model combine to identify and correct lower-level error within components of the system before error escalation can occur. This increased transparency provides more available information for all groups within the entire system, increasing the ability of the system to identify, understand, and mitigate error (Rijpma, 1997, pp. 19-20). Thus, response to error within the model is not limited to a specific organization or group, but is a system-wide response (LaPorte & Consolini, 1991).

Error Shift. Shifting attention from accidents alone toward the identification and mitigation of the precursors of accidents is an important feature in the evolution of the error-intolerant federal aviation regulatory system. As introduced in the literature review, error-intolerant organizations expend considerable time and resources to identify error in the making in order to prevent accidents, looking for and responding to weak error signals in the operational environment and taking action to contain or eliminate error before it escalates into an accident (Weick and Sutcliffe, 2001). These actions are primarily for aircraft accident prevention, with aircraft accidents considered as the primary error. However, as more information was collected over time on events associated with accidents, a slow but steady shift in focus occurred. While accidents will always receive significant attention, occurrences associated with causing accidents were elevated in importance at both the policy- and agency-levels of the aviation regulatory system. Precursor events are regarded as a serious measure of aviation safety program performance and are being reported and analyzed in the same manner as actual errors. This error shift, the treatment of precursive error as seriously as major error, is responsible for obtaining and sustaining the exceptional levels of aviation safety and reliability within the federal aviation regulatory structure. Error-shift is an important concept in explaining why the FAA's ATC service has been able to sustain a high level of safe performance.

WHAT'S BEEN LEARNED FROM EXISTING ERROR-INTOLERANT SYSTEMS

LaPorte and Consolini (1991) stated that highly safe and productive organizational performance is both rare and difficult to sustain, and is theoretically unexplainable. The empirical answer to how error-intolerant organizations are able to perform safely at high operational levels lies in the development and use of error-intolerance attributes (Tables 1 & 2) within an integrated system represented by the Aviation Regulatory System Model (Figure 1).

Using the model and incorporating the appropriate organizational attributes and characteristics enables the building of error-intolerant systems. Though the attributes and characteristics used in this research to identify error-intolerance are in need of further testing and refinement, they provide a framework that can be used to construct and evaluate high performance, low error organizations. It is important to emphasize that first policy-level decision makers must establish and commit to a long-term effort involving allocation of adequate resources to build these systems. It must also be understood that error-intolerant organizations do not exist as unique separate entities. High performance, low error organizations will likely evolve and operate as part of a larger error-intolerant system. Since information flow is crucial to the development and operation of error-intolerant organizations, policy-makers and agency officials must ensure operational transparency by instituting redundant programs that enable the rapid collection and sharing of operational and performance related data.

It is believed that the attributes and characteristics developed within this study are generalizable and can serve as a blueprint for the development of organizational structures and behaviors to aid in error reduction at the policy-level, agency-level, and front-line operational level of any transportation system.

APPLYING THE EI MODEL TO OTHER TRANSPORTATION SYSTEMS

An example of how the EI model can be used to evaluate and improve other transportation systems follows. However, because of the complexity and length required or a full analysis, an abbreviated demonstration of the model follows Federal Highway Administration and its role in promoting safety (controlling error) in the operation of the nation's highway transportation system.

Policy-level Evaluation Exercise:

- The first action required is to use the four policy-level attributes and their associated characteristics to evaluate the policy-level structure and operation of the target transportation system (Table 1). For example, if it is desired to reduce the number of highway fatalities on America's highway system, the first step involves evaluation of the relational structure existing between policy-makers and the Federal Highway Administration (FHA). The degree of *government connection* between policy-makers and FHA agency leadership is indicative of the importance of the regulatory programs to policy makers. If the agency's regulatory program is deemed as important by policymakers, the agency tasked with regulatory duties will enjoy considerable administrative status and linkage to senior policy decision-makers. As part of this analysis it is observed that the operation of the nation's highways do receive considerable attention from policy makers and the federal government imposes highway safety standards. Its regulatory duties primarily entail providing technical and financial support to states and localities for safe construction and improvement of highways. The FHWA, like the FAA, exists as separate agency within the Department of Transportation and its senior leadership may report directly, on occasion, to the Executive and Legislative Branches

- The greater the degree to which policy makers desire to reduce error within a particular public policy area, the more redundant and specialized overlapping *external oversight structure* will be employed to monitor and evaluate regulatory program execution. These specialized oversight bodies are constructed to gather and distribute information from multiple perspectives to provide decision-makers with agency performance information. With such reliable, time information, continual policy-level actions can be taken to reduce or mitigate error within regulatory programs. Importantly, these specialized bodies provide three important oversight functions. The DOT Secretary provides executive-level operational oversight and direction. Error prevention action can be directed to be taken by the agency by the DOT Secretary when error is perceived to be emerging without having to wait for legislative or executive orders. The DOT IG represents a permanent oversight function that ensures that agencies are compliant with legislative and executive intent and monitors agencies for compliance with their own internal rules and regulations. The

NTSB, as an independent body, is tasked solely with error identification and prevention. It evaluates programs and actions and makes recommendations regardless of the political or economic cost. Like the FAA, the FHWA is subjected to oversight and monitoring by these three bodies in addition to more traditional executive and congressional panels, boards, and committees. However, the degree to which FHWA programs are monitored and investigated by specialized boards like the National Transportation Safety Board at this time is unclear. There is no immediate evidence that the FHWA is subjected to periodic directed inspections or audits by specialized external monitoring bodies to decrease program error as experienced by FAA and ATC.

- Funding of agencies conducting critical regulatory programs tends to be consistent and highly supportive. *Resource allocation* for EI organizations is not only adequate to meet agency operational requirements, but is likely to support mission expansion. Current funds from the Federal-aid Highway Program only targets 4 percent of nation's highways, but does contain provisions for additional resources that can be used on another one million urban and rural roads (FHWA, 2009). Policymakers in error-intolerant policy areas will tend to specifically target funding to prevent the occurrence of error. Funding for the nation's highway and bridges is one problem area that has been identified as problematic. Public and political concern over deteriorating roads and bridges indicate that funding has been inadequate to support safe highway operations.

- Some FHWA programs reflect a *safety prioritization* protocol used at the policy-level designed to identify and eliminate elements or precursive events associated with causing or contributing to potential error or failures. Again, EI decision-makers should employ a strategy of multiple, redundant, and overlapping safety programs executed by different organizations in an effort to reduce error from multiple directions. Interestingly, although the executive administration and Congress have shown that they are aware of many of the issues relating to highway safety, they appear to take less aggressive action than in the cause of aviation related error. The latest stimulus package passed by Congress has funded many state and federal highway infrastructure projects targeting areas associated with problem areas associated with vehicle accidents. However, the commitment by policy decision-makers to long-term sustained funding like the FAA has received is not as evident.

The implementation of the operational characteristics of these four key policy-level attributes is indicative of the degree of program error-intolerance sought by senior decision-makers. Error reduction actions by policy-makers to resolve FHA safety system issues requires committed, long-term support by policy makers to be accomplished. The apparent acceptance by government policy makers of over 40,000 traffic fatalities year after year argues against that commitment.

Agency-level Action: Policy-level evaluation and implementation of error-intolerant attributes and characteristics is intended to make the agency-level, regulatory function portion of government perform better to make fewer errors in programs intended to achieve policy safety goals. Just as the examination of the policy-level actions gives an indication of senior decision makers policy commitment to error reduction, an examination of existing EI characteristics within the agency should produce an indication of error-intolerance development within the agency.

- The degree to which an agency's *regulatory structure* is centralized is a critical organizational measure relating to HRO operations. Agencies possessing a well-developed level of EI employ a system of centralized authority and leadership to exercise control over operations. Centralized authority establishes explicit lines of organizational authority, uniform rules to guide internal agency operations and ensure compliance for the regulated community, and formal information gathering and sharing systems. In its quest to reduce error, the EI agency seeks to expand its regulatory footprint, its authority over areas that affect the agency's ability to control error. A review of the FHWA organizational chart (2009) reveals that the administration has a centralized Administrator overseeing the operation of 13 major offices. However, the degree of federal centralized authority that can be exercised over road systems within states appears limited. Safety standards for roads may be promulgated on a federal level, but states exercise considerable autonomy and individuality. States own and operate the majority of highway and road systems and appear to be subjected to minimum central control, particularly when compared to the authority exercised over states in aviation matters by the federal government. The FHWA appears to employ uniform and standardized rules to guide external and internal operations, but is able to exercise only limited regulatory control over rural and urban roads, roads that have been identified as experiencing high rates of highway accidents and fatalities (FHWA, 2009). The extent that information flows vertically and laterally within the FHWA is not immediately available and requires more in depth investigation.

- EI organizations make use of a rigid and intensive *training* framework that is intended to support standardization and compliance. As organizations become more error-intolerant, less trial-and-error training is observed. New organizational members are trained in under a standardized syllabus, often at centralized facilities. Experienced organizational members are required to participate in reoccurring training to ensure that they are proficient in the latest technologies and procedures. Training and professional skills within EI organizations are deemed critical for personnel advancement. While FHWA personnel are undoubtedly required to be technically educated and skilled, a review of the FHWA organizational framework reveals no internal training office, department, or other section that might perform certification, recertification, or ongoing training for professional advancement.

- *Formal system improvement* programs are utilized by EI organizations to continuously reduce error and improve organizational performance. Redundant programs are established within the organization to collect data and evaluate performance. Since performance information is critical to error reduction, incentives and rewards are commonly offered to employees for error related information. It is also common for these improvement programs to offer protection and amnesty for employees reporting problems. Integral to formal system improvement systems are information distribution mechanisms so that data can be rapidly and acted on. A cursory examination of FHWA programs did not reveal any systematic program of internal inspections to improve organizational performance. Evidence does exist that the FHWA is pursuing implementation of proven safety measures (FHWA 2008). However, while this particular program contains audit provisions, the audits are primarily road safety audits (RSA) that focus on examination of current or future inspection of road systems to identify safety problems and associated corrective actions. From the language used in the policy guideline memorandum, it does not appear that the RSA is yet a formalized program or policy. The proven safety measure inventory program contains eight other highway accident (error) reduction strategies that the FHWA encourages states and localities to employ. Importantly, the proven Safety Countermeasures program appears to be largely voluntary. The FHWA additionally does not appear to use redundant and overlapping programs evaluate internal or external performance, nor is there evidence that it offers of rewards, incentives or protection for workers who report safety issues.

- EI organizations performing critical and often hazardous tasks require *specialized personnel requirements* for employment. These individuals are rigidly screened and recruited because of specialized education, skills, or aptitude. Once within the organization, senior specialists will supervise specialized junior personnel. It is common that specialized trade groups and unions frequently represent these workers in work and professional matters. A review of the FHWA job site[2] revealed that the administration was seeking 18 civil and structural engineers, 12 finance and contract specialists, two economists, three administrative assistants, one environmental specialist, two community planners and one equal opportunity human resource expert. This screening does not represent a scientific sampling, but does suggest that the FHWA seeks to employ highly specialized individuals and it is likely that senior specialized personnel direct specialized efforts.

- Another factor key to the operation of the EI agency structure is its internal *communication/decision process*. Policy goals and mission requirements are formulated centrally, but how critical day-to-day operational decision-making is distributed horizontally and laterally within the organization is not immediately identifiable. Regional and local managers who are deemed most qualified have considerable latitude as to what decisions to make in their areas of responsibility. Once again, within the EI framework, information flow throughout the organization is crucial. Lessons learned, best practices, and error prevention ideas are shared by established information sharing mechanisms like newsletters and briefings and are incorporated into periodic personnel training. In addition, emergency systems of communication exist within the structure to disseminate vital information crucial to operational decision-making. A cursory examination of the FHWA did not reveal how much decision-making authority mid-level and local managers possessed within the agency. Further in depth investigation is required to determine the operational need for autonomy in the FWHA.

- Error-intolerant organizations place the highest priority on safety. *Safety prioritization* drives organizations to seek, if not develop technology and procedural protocols to reduce error. Again, multiple and redundant monitoring and safety protocols are created

[2] An audit was conducted in mid Feb 2009 on the FHA job site http://jobsearch.dot.gov/revealing 40 vacant FHWA postions

for error reduction purposes. In fully mature EI organizations safety concerns are prioritized over economic considerations. Actions affecting safe operations are rapidly transmitted and it is not uncommon for operations to be reduced or halted if safety is believed to be threatened. It is unclear if safety within the FWHA is actually considered as equally important as economic considerations. There does not appear to be provisions where the FHWA would halt highway projects for safety. The FHWA clearly seeks to employ emerging technology for error reduction and appears to be attempting to employ multiple strategies to reduce vehicle accidents. The data driven Highway Safety Improvement Program (HSIP) focuses on problem areas associated with accidents (error) while identifying and initiating corrective actions for highway-related safety problems (FHWA, 2006). The number and variance of error reporting mechanisms, utilized by the FHWA, to focus agency programs and resource is not immediately evident and needs further investigation.

- As discussed previously, training is considered to be an important factor in EI operations. Specialized personnel are sought out and carefully screened before they are recruited. Once recruited personnel are expected to maintain extraordinary *technical competence standards.* Certification and recertification of specialized personnel are used to ensure competency. New personnel are often placed in positions with a relatively low level of stress and demand where experience and competency can be accumulated before being placed in more demanding positions. New workers are monitored, mentored and evaluated by specialized personnel designated as trainers to assure competency. To reduce trial-and-error learning, simulation and role-playing are frequently used. Accumulated experience and demonstrated satisfactory technical competence are requisite before the individual is placed in more demanding environments and roles. Again this area needs more in depth investigation than is provided in this paper. However, as was observed at the FHWA job website, the majority of personnel positions sought required certificated engineering and finance personnel. How these personnel are trained or professionally developed once they join the administration is not currently clear, though it is reasonable to assume that experience and demonstration of professional expertise is required for internal advancement.

- Lastly, as has been stated previously, complex EI organizations are well funded. Typical f*unding* not only supports routine agency or organizational operation, but also enables expansion of regulatory operations. Internal funding may also be redirected to areas demonstrating potential for error or failure. Thus, funding is intentionally directed to ensure that error does not occur. Though in the past highway and bridge funding has been viewed as under funded, it appears that the FHWA has been adequately funded to perform its basic mission. There is evidence that the FHWA has directed research and outreach program funding to reduce error in highway design and operation (as demonstrated by SAFETEA-LU), though the degree funds are diverted and the degree to which funding expressly targets error needs further exploration.

USING REGULATORY SYSTEM MODEL TO COMPARE THE FHWA AND FAA

Applying the EI Regulatory System Model to compare the FHWA to the FAA reveals some notable differences. Though the FHWA and FAA share similar structures at the oversight level, the two administrations show notable differences in their regulatory authority. The regulation center section of Figure 1 shows that the FAA holds exceptional regulatory authority over aviation. First, it conducts pervasive licensing, certification, and inspection of virtually the entire aviation industry, controlling manufacturers, mechanics, and pilots, flight schools as well as all passenger and cargo company operations. Next, the FAA is responsible for development, modernization, maintenance, and operation of the nation's aviation infrastructure, airways, airports, navigation aids and all associated technology. Lastly, the FAA operates the nation's air traffic control system, which routinely demonstrates the ability to simultaneously guide thousands of aircraft carrying millions of people from take-off to landing without incident. Because of this error-intolerant federal aviation regulatory system, flying in commercial aircraft in the United States is even safer than riding a bicycle (O'Neil, 2008). In comparison to the FAA, the FHWA appears to have considerably less regulatory power over the ground transportation industry, principally because of the differing policy approach used to guide ground operations and transportation safety.

America's highways and motor vehicle operation and safety are overseen by four independent federal administrations existing within the Department of Transportation. Each administration has separate, but sometimes overlapping areas of responsibility.

- The Federal Motor Carrier Safety Administration (FMCSA) is responsible for overseeing and promoting safe operations of large trucks and buses. It does so by promoting, not dictating, the "adoption and enforcement of State laws and regulations pertaining to commercial motor vehicle safety that are compatible with appropriate parts of the Federal Motor Carrier Safety Regulations" (FMCSA, 2009, np).
- The National Highway Traffic Safety Administration (NHTSA) establishes rules and safety standards for motor vehicles as well as enforcement guidance, technical assistance and training for states for implementation of highway safety plans (NHTSA, 2009). While the federal government sets engineering and safety standards for vehicles, states set vehicle licensing and training and enforcement standards.
- The Federal Highway Administration (FHWA) is responsible for highway infrastructure, "ensuring that America's roads and highways continue to be the safest and most technologically up-to-date" (FHWA, 2009, np). The federal government does not own or operate the majority of the nation's highways, but provides states and tribal governments with significant financial and technical assistance for planning and road construction.
- The Federal Transit Authority (FTA) administers federal grants to support locally planned and operated mass transit systems. Transit systems may consist of buses, subways, light rail, monorail to ferries, railways and various people mover technologies. The FTA by law must perform regular evaluations of grantee programs to assess performance and compliance with Federally determined requirements (FTA, 2009).

As a result of the division of roles, the regulation of ground transportation lacks centralization, where the regulation of aviation is very centralized. This lack of centralization suggests a lack of control over highway and ground operations may be the reason the government has not been able to substantially lower ground accident rates.

Policy makers have employed much different levels of preemptive policy in regulation of ground vehicle operations and supporting infrastructure than has been exercised in control of aviation. The federal government has exercised pervasive preemptive regulatory control over the aviation industry since the late 1930s, beginning with the passage of the Civil Aeronautics Act. Ground transportation has experienced only a limited degree of federal preemption. Individual states still maintain considerable jurisdictional control over ground transportation vehicles, infrastructure, and operations. While the federal government exercises some coordination and control over various aspects of commercial vehicle licensing and safety certification, driver licensing is still primarily a state function. In addition, the certification requirements for personnel driving, manufacturing, or repairing ground vehicles are considerably less stringent. Another significant area of difference is in traffic flow control. There is arguably little traffic flow or sequencing control exercised by states or by the federal government. There is no standardized national traffic control system for ground vehicles that ensures safe separation and operation of ground vehicles or pedestrians. Again, the lack of centralized traffic control, at least at the local or state level, may be another reason that accident and injury rates remain so high.

As stated at the beginning, this paper is an initial and cursory exploration of how to expand the Federal Aviation Regulatory System for use in reducing error in other transportation systems. It is clear that much greater in depth investigation and comparison between aviation and ground transportation systems is needed to reach proper conclusions. However, even a cursory comparison of ground transportation and aviation regulatory schemes reveals some potentially important differences that, if further explored and accepted, could substantially reduce ground transportation accidents, injuries, and deaths.

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