"Design of a Smart, Survivable Sensor System for Enhancing the Safe and Secure Transportation of Hazardous or High-value Cargo on Railroads"

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Abstract – An application of smart sensor technology developed by Sandia National Laboratories for use in the safe and secure transportation of high value or hazardous materials is proposed for a railroad application. The *Green Box* would be capable of surviving most typical railroad accidents. In an accident, the system would send a distress signal notifying authorities of the location and condition of the cargo; permitting them to respond in the most effective manner.

The concept proposes a strap-on sensor package, the *Green Box,* that could be attached to any railroad car or cargo container. Its primary purpose is to minimize the number, severity and consequences of accidents and to reduce losses due to theft. The system would also be capable of recognizing component failure conditions, notifying the operators and logging sensor data for use in directing preventative maintenance.

The modular implementation, which facilitates system integration in a number of applications including the Advanced Train Control System (ACTS), is discussed. The methodology for determining the environmental specification for accident survivability is presented. A test plan for evaluating hardware performance in both normal operating and accident conditions is described.

INTRODUCTION

Sandia National Laboratories has developed a smart, strap-on sensor module for use in the transportation industry [1]. The *Green Box* as it is called, is intended to be the principal component in an automated emergency notification system (AENS) for rail traffic (Figure 1). The main focus is on operational safety, which is accomplished by alerting the vehicle operator of deteriorating conditions in safety critical systems and sending an alarm when an accident occurs.

Applied to railroad traffic, the concept would consist of accident transmitter/receivers mounted on railcars. In the event of an accident, information would be routed through the train's voice/data radio or directly to wayside relay stations. The module will transmit a distress message identifying the location of the accident, a description of the cargo and condition of the vehicle/container. During normal operations, the module's sensors will continuously monitor the performance of safety critical components and report deteriorating conditions to the operators (Figure 2). Based on these reports, maintenance requests can be scheduled to resolve the deficiencies. To avoid communications gridlock only information packets, not raw data, would be transmitted.

The loss of revenue resulting from either unscheduled maintenance or accidents are a major concern to the transportation industry. Experience shows that vehicles that break down during periods of peak operations, particularly in urban areas, can disrupt traffic patterns, introduce long delays and result in increased operational costs. The situation is particularly acute if hazardous materials are involved. Such incidents often precipitate environmental problems where clean-up costs and related damages are sky rocketing [2]. Real-time monitoring of critical components can significantly reduce this problem by identifying declining capability before the failure occurs.

This project addresses these transportation problems. The primary goal is to demonstrate, through field testing and analysis, the benefit of this concept in terms of enhanced public safety and reduced operational costs to the railroad industry. Another goal is to adapt Sandia National Laboratories' intelligent, accident survivable sensor system, the *Green Box,* for use in real-time monitoring and tracking of railcars and their cargo. The project focus is on user requirements, related to the shipment of hazardous and high-value cargo. The device will be designed as a value added component integrated into existing industry systems and standards. The system is a shipper/carrier based alternative to national central reporting systems [3].

INITIAL PROGRAM FOCUS

In the United States, 36 percent of all freight ton-miles are carried by rail. Trains use one third the fuel of trucks to carry the same amount of goods. This leads to lower freight charges and a lowering of the

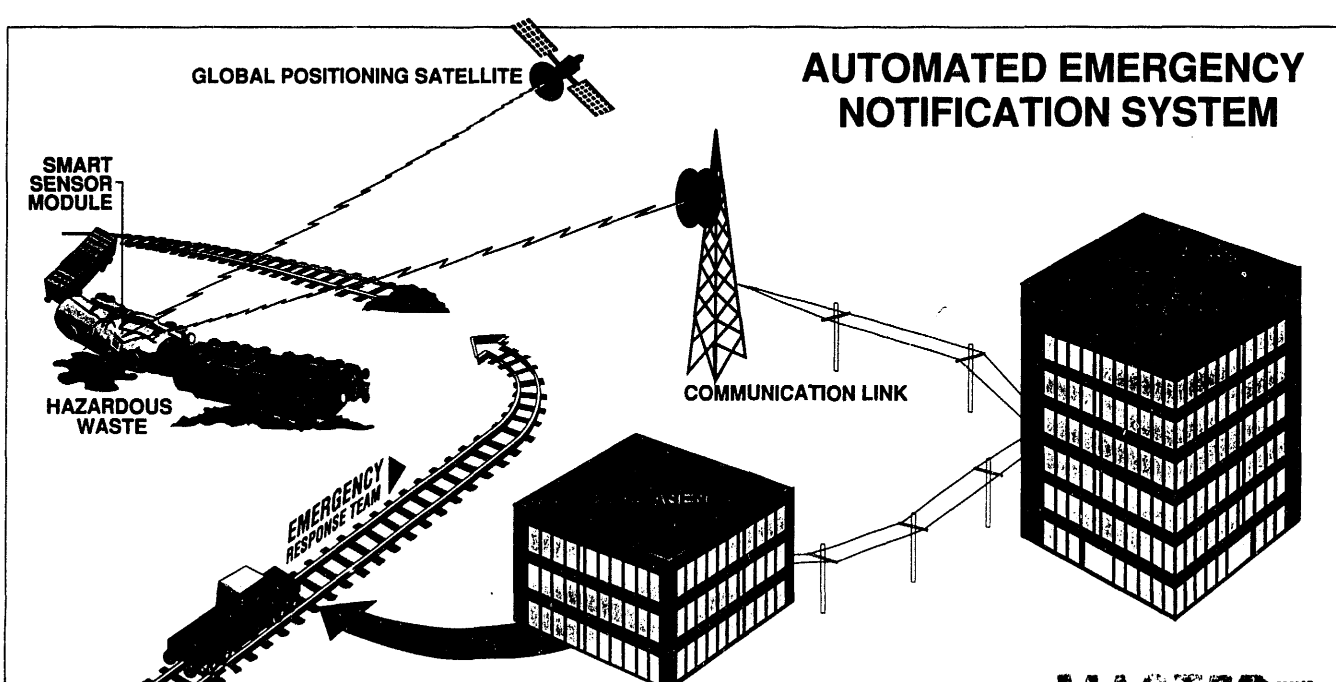

Figure 1. Accident scenario for initiating an automatic distress signal.

Figure 2. *Green Box* in the automated maintenance scheduler mode.

exhaust fume contribution to environmental pollution. As a result, enhancing rail transport and encouraging the shipment of freight by trains will reduce highway congestion, increase highway safety and reduce the frequency of highway repair. The direct benefit of enhancing reliability, safety and quality of rail service is expected to be in excess of $20 million annually. In addition, the railroad industry has a history of cooperation and standardization, principally through the Association of American Railroads (AAR). This facilitates the process of integrating new capabilities into the railroad transportation system. For these reasons, the project is initially focusing on the railroad application, where the *Green Box* would be integrated into the Advanced Train Control System, (ATCS) [4], see Figure 3.

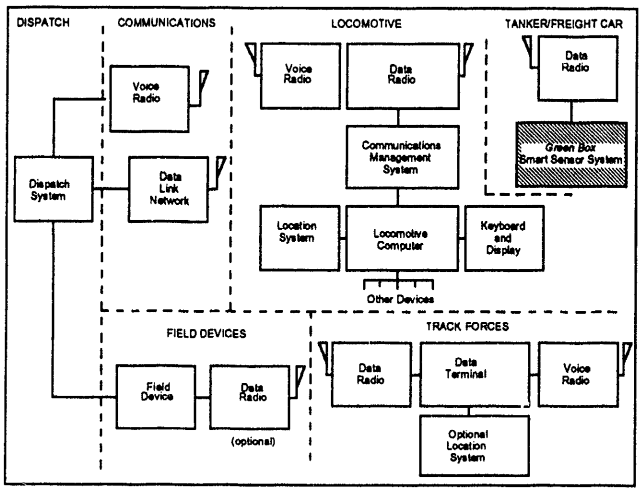

Figure 3. ATCS architecture integrating the *Green Box* sensor system.

THE GREEN BOX APPLIED TO THE RAILROAD

The sensor system will continuously monitor the condition of safety- and security-critical components (e.g., brake temperature, head lights) and report off-normal conditions to the operator. This data will be logged for later review and analysis, similar in principle to the use of flight computers on a commercial aircraft. In the event of an accident, the central controller will recognize the condition and transmit a distress message to the emergency response authorities.

While severe accidents and normal operating conditions can be well characterized, "off-normal" conditions are not easily defined. What is a deteriorating condition? At what point does a drop in performance in the overall system suggest a need for maintenance or safety inspection? An artificial intelligence learning capability in the microprocessor-based central controller will answer these questions. The central controller will examine the sensor inputs and take action based on learned patterns. A collateral and very important benefit of the decision, false alarms will be minimized. Simple sensor system faults will not initiate emergency messages.

The sensor system can be particularly useful in identifying conditions that accelerate wear or degrade performance. Problems are not always evident during static inspections. The sensors, for example, can identify intermittent problems that occur only when the equipment is operating under load. The smart sensor will be able to detect these conditions, log the information and help expedite the repair process. As a result, the frequency, time and cost of repairs should be reduced. By identifying the need for maintenance before a catastrophic failure occurs, other costs such as cleanup costs and loss of life can be avoided.

The *Green Box* modular design permits us to integrate the smart sensor system with the ATCS system architecture. Cars transporting hazardous materials would be fitted with strap-on sensor modules which monitor both cargo and vehicle state-of-health. In the case of containerized cargo or "piggy back" freight, the module could be attached directly to the container or truck-trailer.

In normal operations, sensor information would be relayed through the locomotive and wayside transceivers to the operations centers. Power for routine operations would be provided by power take-offs on the train's axles. If an emergency condition were detected (determined *a priori* by the user), the *Green Box* would transmit directly to the wayside communications network. In the future this could be accomplished by low earth orbit (LEO) satellite links (Figure 4). The sensor selection, threshold values, sensitivities, operating environments, etc. would be defined by the end user. Power during emergency transmissions would be provided by internal batteries.

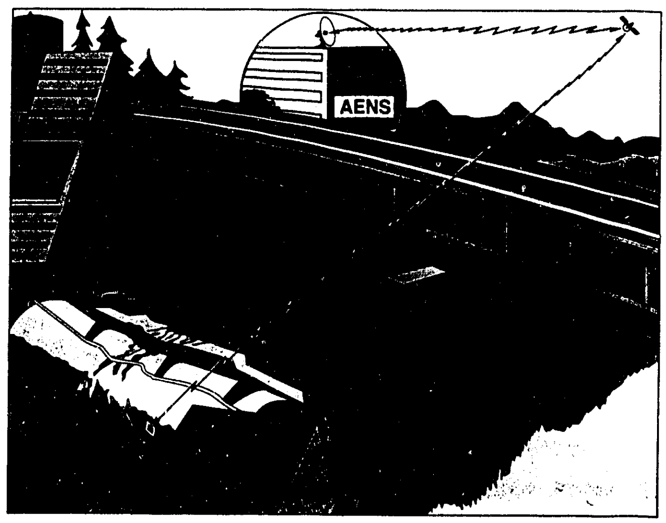

Figure 4. Emergency notification via low earth orbit satellite link.

Finally, the use of the *Green Box* can assist in scheduling maintenance. In complex systems where accurate analytic models are very difficult or impossible to develop, an intelligent system is useful. The *Green Box*, for example, might use "learned information" to evaluate acceptable system performance in circumstances in which the exact interpretation of deteriorating performance is uncertain. If statistical data on the performance of equipment is available, the smart sensor can use historic data to establish a baseline, then establish new trends as additional data are logged.

ELECTRICAL DESIGN IMPLEMENTATION

The *Green Box* electronics design is based on a modular approach to maximize flexibility and allow the *Green Box* to be used in a withstand se·ere environments. Typical operating conditions for weapon components include shock environments over 20,000 g's, vibration over 30 grms, temperatures to 200 °C and hundreds of g's acceleration. Packaging techniques used to survive these environments include foaming or encapsulation for the mechanical environments and high temperature soldering techniques for thermal environments. Some or all of these techniques will be applied to the *Green Box* design.

For the SMARTS package, each of the modules is a printed circuit board assembly. The mechanical form factor is flexible to allow mixing and matching capabilities as needed. Modules are stacked and interconnected by square post headers on a socket strip. Three socket strips with 50 sockets are included per module. High density MDM connectors are used to interface the modules externally.

DESIGNING FOR SURVIVABILITY

The objective is to produce a component (housing and electronics) that will survival the initial accident event and immediately report critical information to the response team. To establish the design specs one must first identify the combination of environments encountered in a typical accident. Unfortunately, such information is scarce. Fully instrumented, simulated railroad accidents are few and the real events are characterized only through postmortem analysis. To complicate matters, important environments such as fire and crush are often available only indirectly through probabilities of occurrence (Figures 7 and 8). In the absence of definitive information, initial survivability specifications have been derived from a combination of sources. These sources include the Federal Aviation Administration (FAA) flight recorder (Black Box), a report prepared for the U.S. Dept. of Energy titled "Severities of Transportation Accidents" and private discussions with experts in the transportation safety industry. The preliminary features are described below.

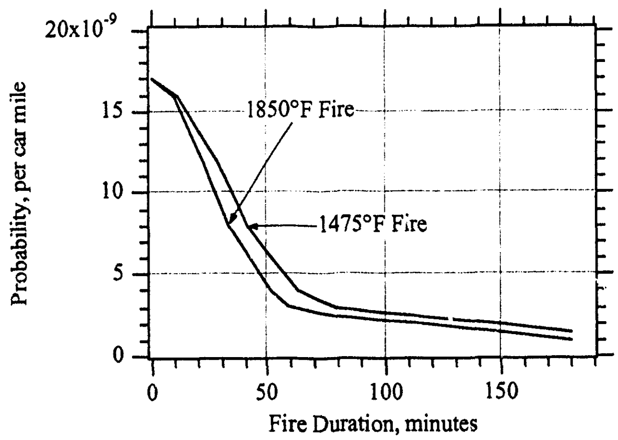

Figure 7. Event probability for railroad accidents involving fire.

Preliminary Design Features

Consistent with the evolving nature of accident environment, the *Green Box* mechanical design philosophy is to produce specifications a durable system while minimizing size and weight. The general requirements are listed in Table I and the environments are listed in Table II. The environments were derived from field measurements of railcar environments [6, 7], Bay Area Rapid Transit environmental specifications [8], FAA Black Box crash survival requirements [9], and environments used for missile component design [10].

The preliminary design is an internally insulated, welded stainless steel box containing the microprocessor, shock (collision) sensor, orientation (rollover) sensor, and temperature (fire) sensor, shown in Figure 9. The estimated weight of this assembly, including electronics, is 45 lbs. External modules containing the batteries, GPS receiver, and communications transmitter/receiver may be bolted to this box as indicated in Figure 9, or may be completely separate structures.

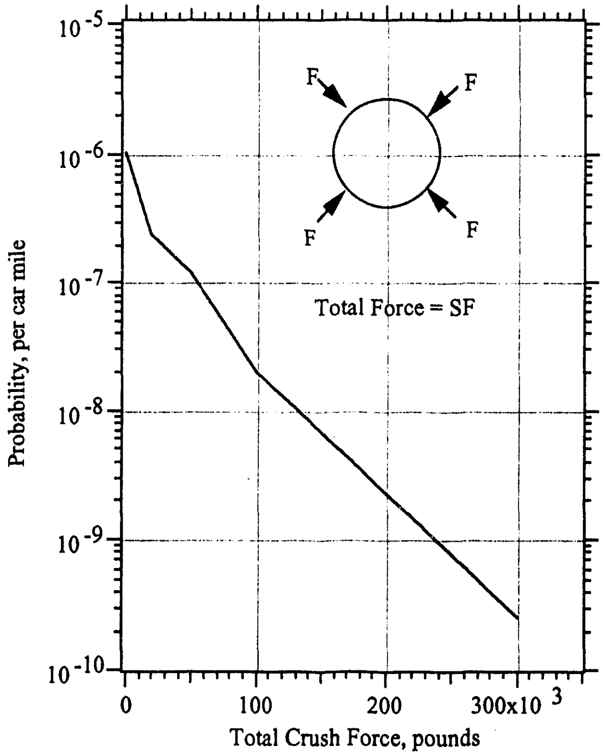

Figure 8. Event probability for railroad accidents involving crush.

Table I. *Green Box* general requirements

Requirement	Specification
Weight	Entire system to weigh 60 lbs or less.
Size:	Not to exceed 12" x 12" x 12".
Electrical Connections	All external connectors to be female. Minimum pin size TBD.
Mechanical Fasteners:	Lids and components: 160,000 psi UNF series hex screws. Attachment to vehicle: 160,000 psi UNC series Hex bolts.
Manufacturing:	Avoid exotic materials and fabrication processes. Allow for modularity.

The *Green Box* housing is being analyzed for compliance with the environments listed in Table II, with specific emphasis on fire and crush. A plastic model has been built to support packaging and form factor for the electronics, sensors, and cabling fit.

Additional Green Box Packaging Issues

It will be important to determine the most survivable location for mounting the *Green Box* on railcars. This issue can be resolved only with the aid of industry input. By judicious location of the *Green Box*, the railcar's inherent crush and shock mitigation features will contribute to its survivability in mechanical environments. There are several competing interests; not all the *Green Box* components have the same mounting requirements. The electronics package, for example, can be stored behind protective barriers to enhance survivability. Antennas, on the other hand, must be mounted externally. Survivability requirements will be established jointly with the end user, the results of computer analyses and test data.

Table II. *Green Box* environments

Environment	Specification
Accident Environments	
Static Crushing Load:	100,000 pounds applied with a 3 inch bar. See Figure 10.
Fire:	Internal electronics must not exceed 200°F after 30 minutes in a fire creating a surrounding blackbody environment at 1850°F.
Shock	Per FAA TSO-C51a.
Penetration:	Per FAA TSO-C51a.
Immersion:	Leak rate in water less than TBD ml/hr. Enclosure and seal materials must be compatible with or resistant to acids, bases, solvents, oxidizers, and fuels.
Combinations of Accident Environments:	The following combination of accident environments shall be considered: 1. Shock, crush 2. Shock, crush, fire 3. Shock, crush, immersion 4. Penetration, fire 5. Penetration, immersion
Normal Operating Environments	
Temperature:	-40°F to 120°F ambient air temperature.
Humidity:	0 to 100% relative humidity.
Vibration:	Accept per specification in Figure 11.
Shock:	Accept per specification in Figure 12.
Weather:	Unit must be designed for exposure to sun, rain, and snow.

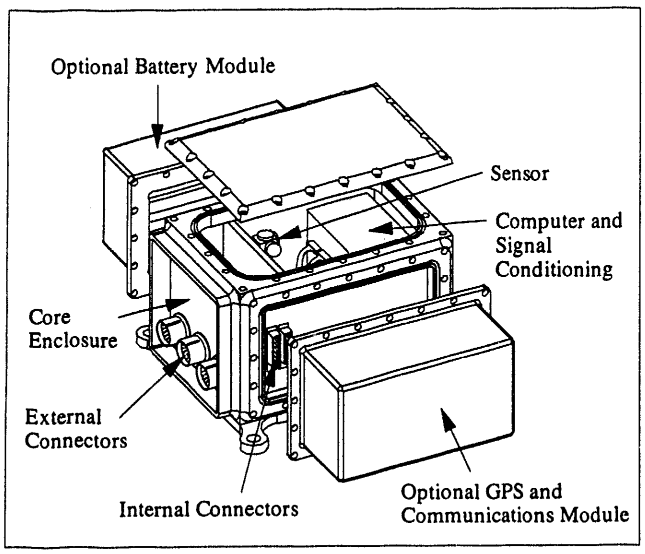

Figure 9. Prototype *Green Box* housing.

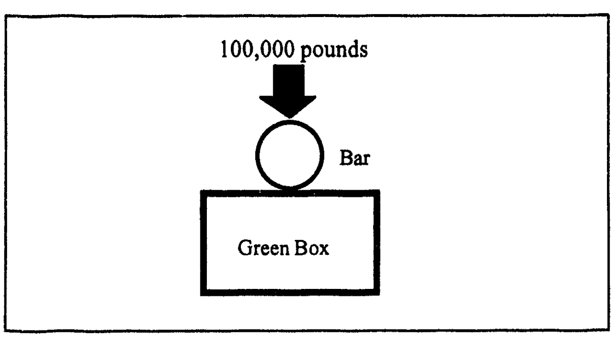

Figure 10. Static crush loading of the *Green Box* housing.

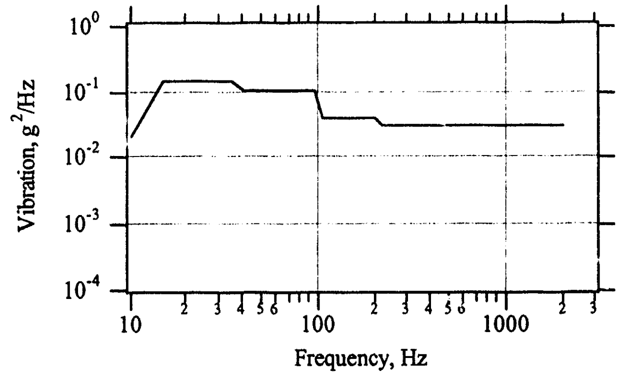

Figure 11. *Green Box* normal environment acceptance random vibration. Apply for 20 seconds on each axis.

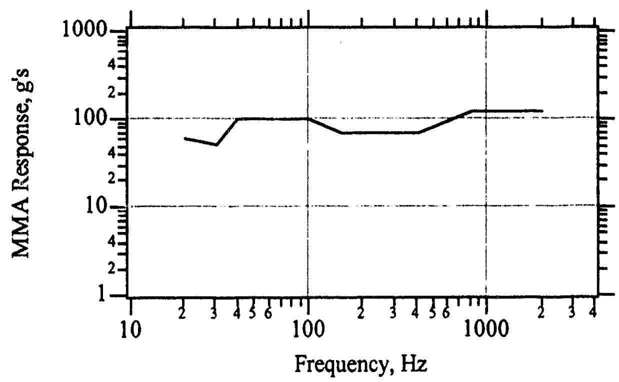

Figure 12. *Green Box* normal environment acceptance shock spectra. 5% damped maxi-max absolute shock spectra. Applied to each axis with decayed sine wavelets on electromagnetic shaker table.

THE TESTING PROGRAM

As discussed above, several well defined packaging and electrical compatibility issues need to be resolved before the *Green Box* design can be finalized. The electrical and mechanical system testing programs are designed to answer them.

Electrical System Testing

To date, the principal *Green Box* modules (Figure 5) have been functionally tested at the component and subsystem level. The SMARTS is a fully developed component with complete drawings, board layouts and production specifications. A prototype strap-on module and base station have been built. The basic functions of the *Green Box* automated monitoring and tracking system have been tested in both laboratory and field demonstrations. In these concept validation tests, ac/dc converters, and rechargeable batteries supplied the necessary system power, and a cellular telephone simulated the communication link. To verify component integration with existing railroad communication and power system interfaces, a full scale functional test in an operational scenario is planned. Both maintenance and simulated emergency conditions will be examined.

After completing this basic electrical system testing, attention will turn to verifying the design meets specific customer requirements. These specific user requirements will be tested as necessary to qualify the system design for that application. As an example, should a customer choose to monitor the shipment of liquid phosphorous from the production plant to the manufacturing facility, one might include a water level sensor on the P_2 tank car in addition to the standard suite of fire, crash and rollover sensors [11]. Furthermore, one might attach a customized transmitter to the communications module that could report directly to the phosphorus emergency response team operations center.

Mechanical System Testing

The mechanical testing program for the *Green Box* is in the planning stage. Working with industry experts (AAR's TTC and the Safety Division of the California Public Utilities Commission, these areas of testing have been identified: normal environment, human engineering and survivability. For normal environments the prototype structure shown in Figure 9 will be fabricated in metal and loaded with mass mocks of the electronics. This assembly will be subjected to the normal environment thermal, vibration and shock conditions to establish the natural responses and to refine the initial design features. This unit will also be used to assess human engineering design features such as *Green Box* maintenance, mounting, connectors, etc. A second assembly with functional electronics will be subjected to both static and dynamic environments to assess the mounting and packaging features of the design.

To validate the survivability of the *Green Box* a series of single environment laboratory tests stressing the design in fire, shock, static crush and high vibration are planned. These tests will be used to match the design with the requirements and to establish the parameters for a fully instrumented, simulated train wreck involving combined shock, crush and fire. We hope this latter test can be incorporated as a joint venture between Sandia National Laboratories and the American Association of Railroads in a simulated train derailment which has been proposed by the TTC.

CONCLUSIONS

An accident resistant, strap-on electronics module has been proposed for use in the railroad industry. The device can autonomously track and monitor the condition and location of high-value or hazardous cargo as well as the condition of the railcar in which it is carried. This information can be used in routine reports to schedule maintenance, expedite shipments and, in an accident, automatically transmit information vital to the emergency response teams,

The primary purpose is to minimize the number, severity and consequences of accidents and to reduce losses due to theft. The system would also be capable of recognizing component failure conditions, notifying the operators and logging sensor data for use in directing preventative maintenance. Taken together, these two features suggest a device that can assist the railroad industry in reducing operating costs and streamlining the flow of traffic by making use of real-time information from the moving railcar and its cargo.

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