

*High-Speed Rail IDEA Program*

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## **Method to Warn Workers of Approaching Trains**

Final Report for High-Speed Rail IDEA Project HSR-4

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*February 1997*

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**TRANSPORTATION RESEARCH BOARD**  
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# **IDEA PROJECT FINAL REPORT**

Contract HSR-4

IDEA Program  
Transportation Research Board  
National Research Council

February, 1997

## **Method to Warn Workers of Approaching Trains**

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Raven, Inc.



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## TABLE OF CONTENTS

<b>EXECUTIVE SUMMARY .....</b>	<b>1</b>
<b>IDEA PRODUCTS-PRODUCT DESCRIPTIONS .....</b>	<b>2</b>
IDEA PRODUCT-MAINTENANCE WORKER WARNING SYSTEM .....	2
<i>Industry Need.....</i>	<i>2</i>
<i>Concept and Innovation-Remote Detection Alert System.....</i>	<i>3</i>
<i>Concept and Innovation-Local Detection Alert System.....</i>	<i>3</i>
OTHER APPLICATIONS OF THE LOCAL TRAIN DETECTION SENSOR.....	4
<i>Industry Need-Alert Sensor at Automobile Crossing.....</i>	<i>4</i>
<i>Industry Need-Positive Train Control .....</i>	<i>5</i>
IDEA PRODUCT-TRAIN INSPECTION .....	5
<i>Industry Need.....</i>	<i>5</i>
<i>Concept and Innovation-Automatic Pre Inspection Evaluation System.....</i>	<i>6</i>
<b>INVESTIGATION-TECHNOLOGY REQUIREMENTS .....</b>	<b>6</b>
<b>TECHNICAL OVERVIEW .....</b>	<b>7</b>
VIBRATION AND WAVES IN ELASTIC MEDIA.....	7
DETECTOR OPERATING CHARACTERISTICS .....	9
<b>RESULTS OF INVESTIGATION.....</b>	<b>10</b>
RANGE OF DETECTION .....	10
TRACK RELATED EFFECTS .....	11
TRAIN RELATED EFFECTS .....	13
<b>PLANS FOR IMPLEMENTATION .....</b>	<b>15</b>
<b>CONCLUSIONS.....</b>	<b>15</b>
<b>APPENDIX A: THEORY OF RAIL VIBRATIONS .....</b>	<b>17</b>
<b>APPENDIX B: DETECTOR OPERATING CHARACTERISTICS .....</b>	<b>19</b>
<b>REFERENCES .....</b>	<b>20</b>

## EXECUTIVE SUMMARY

The objective of this project was to investigate the potential utility to the railroad industry of exploiting train induced rail vibrational signals. In Stage 1 rail vibrational data was collected and analyzed. It was found that the trains stimulate a rich vibrational signature related to several properties of the train. The primary goal of the project was to develop a passive device for warning maintenance gangs of approaching trains. In Stage 2 several potential applications of the basic technology were addressed:

1. A flagman assistance device,
2. Automobile crossing sensors,
3. Sensors for improved traffic control, and
4. Devices for performing automatic pre-inspections.

Prior to the field testing a literature search of rail vibration information was conducted. General theories were reviewed of vibrations and wave propagation in a rail. From this information a system was fabricated for field test data recording. A piezoelectric based accelerometer with a mounting magnet was chosen which has a flat frequency response across the band of interest. The data was recorded on a laptop computer after digital sampling.

Data was recorded at several locations under the supervision of either a CSX and WMATA flagman. Freight, passenger, and commuter transit trains were included. Speeds of the trains varied from rest to over 70mph. The analysis results reflect the complexity of the vibrational signal spectra and the geometries involved. Train induced signals included both broadband and narrowband information. The broadband characteristics are related to transients or bangs possibly attributed to wheel or rail smoothness discontinuities. Other train-induced signals stimulated narrowband vibrational signals in the rail. Most of the narrowband signal frequencies were seen to be directly proportional to train speed and generally more local to the train. Other signals were the result of train vibrations such as that caused by moving on a curved track at high speed.

These various signals can be used in several ways to aid the railroad industry. The signals can be used to detect the presence of a train at some distance from the sensor or at the sensor. This attribute led to the design of two different devices that can be used to alert a flagman that a train is approaching a maintenance crew. These same devices can be adapted as an inexpensive means of operating a warning system at an automobile crossing. The local train detection sensor with or without adding the ability to extract the speed information can be an inexpensive means of positive train control for improving the system traffic control. Finally, a simple device can be based on this technology which can identify any cars causing high rail impact for later manual inspection. Any or all of these devices can assist in making the rail system safer and more profitable.

## **IDEA PRODUCTS-PRODUCT DESCRIPTIONS**

The objective of this project was to investigate the potential utility to the railroad industry of exploiting train induced rail vibrational signals. In Stage 1 rail vibrational data was collected and analyzed. It was found that the trains stimulate a rich vibrational signature related to several properties of the train. Particular needs of the railroad industry have been selected through discussions with industry personnel during this IDEA project. Designs of product prototypes have been considered to illustrate the potential utility of train induced rail vibration technology to improving safety and profitability. The designs include an accelerometer, which is attached either by a clamp or magnet together with a processor and user interface. Although the primary goal of the project was to develop a passive device for warning maintenance gangs of approaching trains, in Stage 2 several potential applications of the basic technology were addressed:

1. A flagman assistance device,
2. Automobile crossing sensors,
3. Sensors for improved traffic control, and
4. Devices for performing automatic pre-inspections.

In the following sections general descriptions of each of these products is presented with the performance requirements. The descriptions are presented in terms of detection capability, tracking capability, or diagnostic capability.

## **IDEA PRODUCT-MAINTENANCE WORKER WARNING SYSTEM**

### **Industry Need**

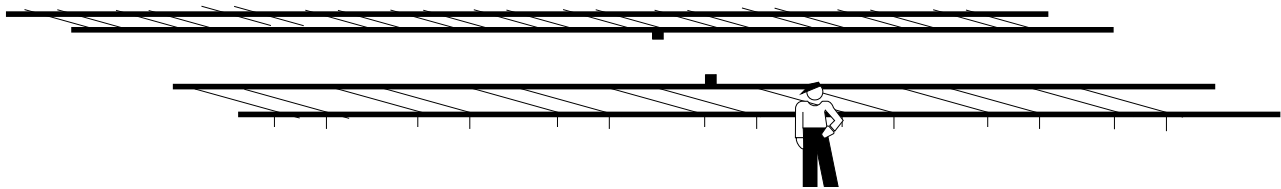
Railroad workers must often be on or near tracks that are supporting active traffic. A safety concern of maintenance gangs on the rails is the approach of trains either on the work rail or on an adjacent rail. More than 50 track workers have died in train accidents over the last 10 years. Depending on the conditions of the work area and type of work, different warning systems exist to alert the gangs to move themselves and their equipment off the tracks. Worker safety is the responsibility of the flagman at the work site. For each work crew a flagman is designated to alert the workers of approaching traffic. His primary train detection is via visual and audible surveillance. Depending on the local environment the audible detectability of the train may be limited, especially with snow on the ground to further dampen the sound propagation. He also monitors the radio communications between the dispatcher and the train engineers. However, the signals may be infrequent or subject to interference. At times, flags are placed at a distance from the work site (in both directions) to provide a visual alert to the train engineer that he is in a work area. A similar method, that alerts both engineer and flagman, uses a small explosive device called a torpedo on the track. The train causes the torpedo to activate resulting in a loud, but harmless bang. Two types of devices to aid the flagman have been developed during this project.



### Concept and Innovation-Remote Detection Alert System

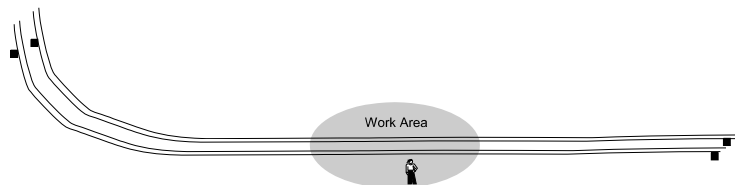
One approach to a train alert system is a device attached to the rail in the vicinity of the work crew or flagman (*Figure 1*). The device detects the presence of a train within a prescribed distance of the sensor. For example, a train approaching at 60 mph would traverse 1 mile in 60 seconds or 2 miles in 120 seconds. A train moving at 30 mph would take twice as long. As an emergency backup to the normal flagman procedures 60-120 seconds should provide enough time to get all of the workers off the tracks. Since the flagman will ignore a device if it is prone to false alarms, detection must be very reliable. These statements can be quantified as detector operating characteristics. The inexpensive device must operate for more than 10 hours without a false alarm and provide a probability of detection of better than 99% for trains within 2 miles. The system would require multiple sensors (one for each track) on a single monitor, which would be interfaced with the standard flagman radio.

*Figure 2* illustrates the design. The device is attached to the rail via a magnet or clamp. The



**FIGURE 1:** *Illustration depicting the general location of sensor devices for the remote detection alert system.*

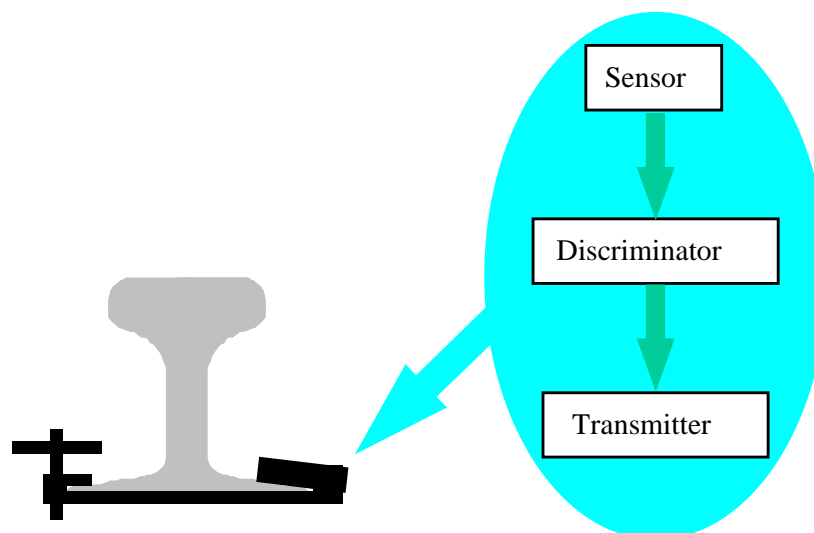
vibrations are detected via the sensor and analyzed for train presence. If a train is coming towards the workers an alert signal is sent to the flagman's radio.



**FIGURE 2:** *Device concept for train detection alert system.*

### Concept and Innovation-Local Detection Alert System

An alternative design to the above system is to place the sensors at the location of the warning flags much as the torpedo is presently used. The device detects the train within 0.5 miles of the sensor or several miles from the flagman as shown in *Figure 3*. Twice as many sensors are required to cover both sides of the work area, and the wireless communication distance is greater. Fortunately, the device is impervious to track induced signal attenuations such as insulated joints, and the system processing requirements are simpler than the remote design. On the other hand, this design puts more stringent requirements on the wireless communications to the flagman. Previously developed systems, such as the Road Crew Portable Laser Warning System, have demonstrated the affordability of the communications technology. (See IDEA Annual Progress Report 1, pages 68-71, December, 1994.)



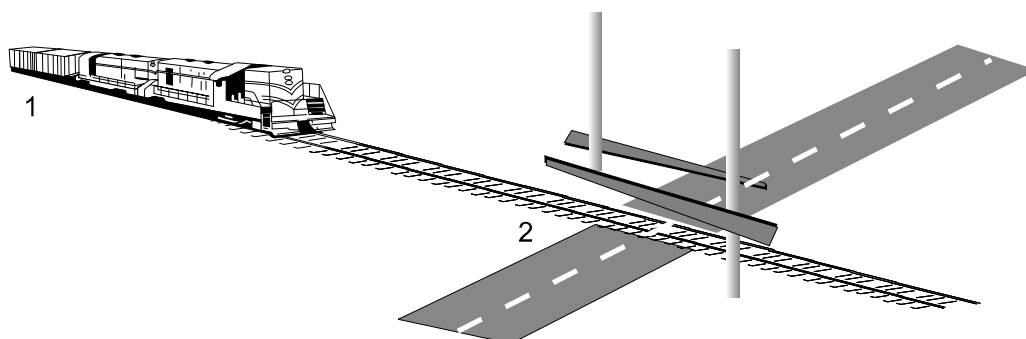
**FIGURE 3:** *Illustration to show the relative locations for devices of a local detection system.*

## OTHER APPLICATIONS OF THE LOCAL TRAIN DETECTION SENSOR

### Industry Need-Alert Sensor at Automobile Crossing

The gates at automobile crossings are activated by several techniques, however, only one third of the crossings in the US are equipped with gates or lights. In 1995 there were almost 600 deaths and almost 2,000 injuries at US rail crossings. One technique is to place a switch on each side of the crossing at a sufficient distance to activate a warning light and possibly a gate that secures the crossing based on the fastest permitted train traffic for the area. Some systems use electrical conduction between the train's wheels and the rail for determining the presence of a train. With the advent of faster trains and the Intelligent Transportation Systems (ITS), the safety of many crossings will need to be further improved. A low cost, but reliable, sensor system would make it feasible to equip more crossings with automatic signals.

The technology of rail vibration train detector can be used as an inexpensive sensor at automobile track crossings. (See *Figure 4.*) Either of the previous designs would suffice; local or remote (location 1 or 2, respectively, in the figure). Such a device would provide increased safety, especially at presently unprotected crossings.



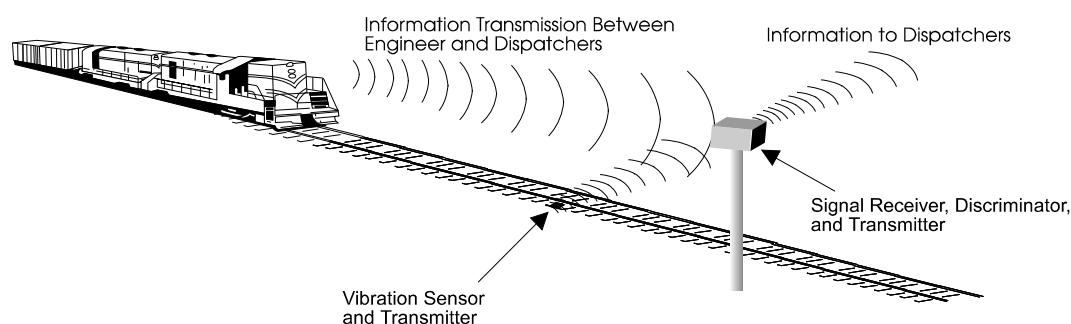
**FIGURE 4:** *Relative device placements for a track crossing signal system.*

## Industry Need-Positive Train Control

Current rail traffic control systems provide dispatchers with train location based on the train's presence on a block of track (often several miles long). The dispatcher directs the engineer from one block of track to the next by means of signal lights and radio communications. The present sensing system is reported to be expensive to maintain and only provides a coarse measure of location. Areas of high rail traffic support more than just freight trains. Commuter, passenger, and freight trains travel on the same rail system. The traffic control dispatcher must efficiently guide these various trains through congested, high traffic areas without the compromise of safety. A more positive train control system would result in improved safety and increased revenues. Several technologies including both on train and on rail systems are being studied to improve the traffic control system. Examples of technologies being studied include GPS and optical navigation systems on the trains plus various electrical and optical sensors on the rails.

Another use of the train induced rail vibration analysis technology would be as part of a system to provide improved traffic control through positive train control. The benefits are improved safety and increased revenues. An inexpensive sensor requiring low maintenance could be placed every 2 miles on the track and provide positive location within 1000 feet to an accuracy of better than 10 feet. In addition a simple algorithm would provide speed estimates of better than 3 mph. The sensor could also provide acceleration information from changes in the narrowband spectral characteristics.

*Figure 5 illustrates a suggested architecture.*



**FIGURE 5:** *Illustration of potential rail traffic control systems.*

## IDEA PRODUCT-TRAIN INSPECTION

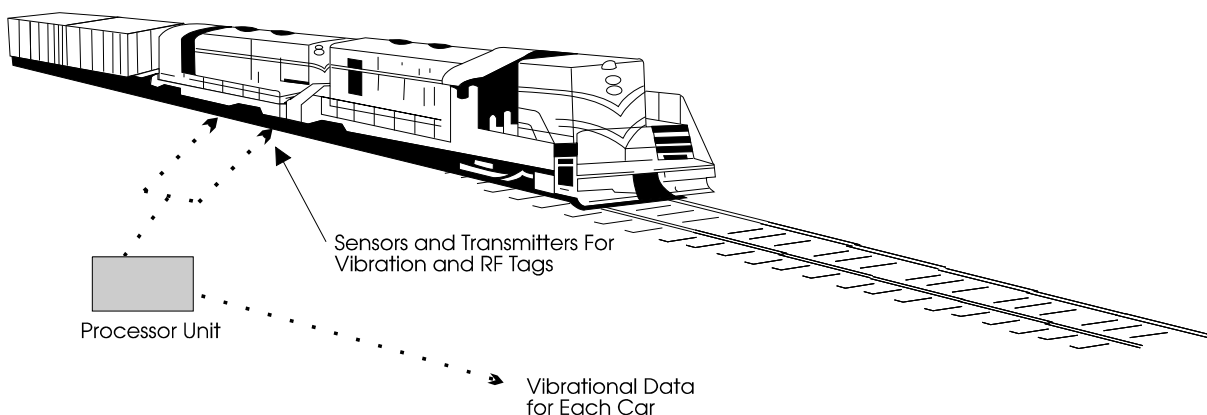
### Industry Need

To maintain safety and efficiency of the rail system both the railroad industry and Federal Railroad Administration (FRA) inspectors need to inspect all of the cars periodically. The FRA has about 400 inspectors responsible for more than 1.2 million cars on over 300,000 miles of track. Inspectors employed by the railroad industry can take over 5 minutes to properly inspect the braking system on a single car. A freight train with over 150 cars may take 12.5 hours to inspect the braking system alone. An automatic pre-inspection system would be beneficial to highlight equipment deficiencies at periodic locations on the rail system. The devices would identify particular and common problems that greatly increase train and track wear and, subsequently, operating costs. Broken wheels, eroded rims, and overheated bearings caused more than 100 accidents in 1995.

Automated inspections not only will increase safety but will also reduce operating costs. For example freight car wheels in revenue service with tread irregularities can cause high impact loads and cause damage to track structures and rail vehicles. Thus, these wheels are removed from service under AAR Rule 41A based upon a visual inspection. An automatic pre inspection system would minimize costs by improving the inspection efficiency. Existing wheel impact detection systems utilize multiple accelerometers and complex processing systems.

### Concept and Innovation-Automatic Pre Inspection Evaluation System

An increasingly popular means of quality, non-destructive inspection in many other industries is vibrational analysis. A pre-screening system would help to prioritize inspection needs. Currently at various sites on the rail system, an RF tag system automatically identifies particular cars of a passing train. Combining this with an automatic vibrational analysis system can provide a means of pre-evaluating the integrity of train cars and identifying priority needs to the inspectors in a manner similar to medical triage. The results of this project have shown that an inexpensive device, which measures the variability of the rail vibrations, can reliably identify cars generating high impact. The performance criteria can again be expressed as a detection requirement. The device correctly identifies 99.9% of the cars with faults while misidentifying 1 of each million cars. The suspect signature and car ID together with the location and date are made available to the inspectors indicating the need for a thorough manual inspection (see *Figure 6*).



**FIGURE 6:** *Illustration showing the application of vibrational information to train inspections.*

## INVESTIGATION-TECHNOLOGY REQUIREMENTS

Each of the first three applications mentioned above (flagman assistance, grade crossings, and traffic control) requires either a remote or local estimate of the presence or of the location of a train relative to the sensor. Additional information about the type, length, speed, and direction of the train may also be worthwhile and can be provided via vibrational analysis. The fourth application requires the system to identify particular features of the car's vibrational spectrum as possibly related to a substandard quality part for later detailed manual inspection.

These applications were each investigated more fully in prior project reports and briefings. Prior reports include discussions of the theories of rail vibrations and feature detection as well as discussions of the results of field test measurements performed during this study. The results are summarized below. In this report descriptions are provided for several devices which can improve the safety of the rail system. The analysis of these applications led to technical requirements, which are summarized in *Table 1*. Designs for prototype devices that meet these requirements were developed using the vibrational analysis results of this IDEA project.

Requirement	Industry Needs	Specification
Remote detection	<ul style="list-style-type: none"> <li>Flagman alert</li> <li>Crossing sensor</li> </ul>	<ul style="list-style-type: none"> <li>Less than 1 false alarm per 10 hours</li> <li>Probability of detection 99% at 2 miles</li> </ul>
Local Detection	<ul style="list-style-type: none"> <li>Flagman alert</li> <li>Crossing sensor</li> </ul>	<ul style="list-style-type: none"> <li>Less than 1 false alarm per 10 hours</li> <li>Local probability of detection of 99%</li> </ul>
Localization and detection	Positive traffic control	Locate to +/- 100 feet
Spectral analysis	Pre-inspection	Critical spectral discriminants

**TABLE 1:** *Industry needs and technical requirements summary of possible applications of vibrational signals in the rails.*

## TECHNICAL OVERVIEW

The notion of vibrations traveling via the rails is not a new idea. It has been said that the rails can be ‘heard singing’ as a train approaches. However, the technology that makes the measurement and analysis of vibrations in such structures practical has become available in recent years. This study made use of previously documented theories as a basis for what vibrational signals and characteristics may be encountered during the field test. A data acquisition system (described in the Stage 1 report) was tailored to measure and store these characteristics.

### VIBRATION AND WAVES IN ELASTIC MEDIA

The classic wave equation for vertical displacement at position  $x$  and at time  $t$  can be written as:

$$\frac{\partial^2}{\partial t^2}\eta(x,t) + \gamma \frac{\partial \eta(x,t)}{\partial t} - \frac{1}{c^2} \frac{\partial^2 \eta(x,t)}{\partial x^2} = F(x,t)$$

where

$\gamma$  is the damping coefficient,

$c$  is the speed of propagation, and

$F(x, t)$  is proportional to the forcing function.

The solution is a non-dispersive summation of wave components. A solution of the homogeneous equation [ $F(x, t) = 0$ ] is the sum of the damped, oscillatory Fourier components. The amplitudes and phases of the components can be computed from the initial conditions. The complete solution of the forced wave equation depends on the particular form of  $F(x, t)$ . Our interest is in the time history of vibrations at a particular position,  $x$ .

A simple model of rail vibrations corresponds to classical flexural waves in beams (Bernoulli-Euler Theory) on a damped, elastic foundation. For simplicity, assume the vertical displacement of the rail obeys the following equation:

$$\frac{\partial^2}{\partial t^2} \eta(x, t) + \gamma \frac{\partial \eta(x, t)}{\partial t} + \beta \eta(x, t) + a \frac{\partial^4 \eta(x, t)}{\partial x^4} = F(x, t)$$

where

$\rho A$  is the mass per unit length ( $x$ ) (the mass density multiplied by the cross-sectional area),

$\beta$  is the stiffness or restoring force constraint divided by  $\rho A$ , and

$a$  is  $EI/\rho A$  where  $E$  is Young's Modulus and  $I$  is the moment of inertia.

Five specific cases will be briefly considered:

- |   |                                  |
|---|----------------------------------|
| Case 1: $F(x, t) = 0$                             | (homogeneous equation),          |
| Case 2: $F(x, t) = f(x-x_0)*\delta(t)$            | (impulse at $x=x_0$ and $t=0$ ), |
| Case 3: $F(x, t) = F_0*f(x-vt)$                   | (moving source),                 |
| Case 4: $F(x, t) = F_0*f(x-vt)*\exp(i\Omega_0 t)$ | (vibrating source), and          |
| Case 5: $F(x, t) = F_0*f(x-vt)*\exp(ik_0 x)$      | (spatially modulated source).    |

Again the solutions can be derived from a modification of the Fourier components of the spatial forcing function or the initial conditions. One of the primary differences between the solution to the classical wave equation and the beam wave equation is that the resultant waves are dispersive (i.e., waves of higher frequencies or shorter wavelengths propagate faster). It should be noted that the speed of sound propagation in steel is almost 5 times the speed of sound in air.

The details of the several examples of potential interest are in the Appendix A. Case 1, the homogeneous equation, and Case 2, the impulse, are solved in standard texts and need not be repeated. The main result from the homogeneous equation is that the signals will propagate along the rail although with distortions resulting from both the mediums (amplitude and phase modifications as well as dispersion and damping effects). Thus, impulses or transients should be present. The steady state solution to Case 3 results in oscillations at frequencies determined by a 'snapshot' of the forcing function ( $f$ ) and the speed of the train (frequency =  $v/\text{wavelength}$ ). Therefore, as a train passes by the sensor speed changes will be reflected in frequency changes of the spectral components. The solution to Case 4 results in a steady state term that includes oscillations at  $\Omega_0$ . Thus, any onboard train vibrations may stimulate vibrations in the rails. The solution to Case 5 adds a vibration or signal modulation which is related to the speed of the train and the and a spatial modulation such as sleeper spacing (frequency =  $v/\text{spacing}$ ).

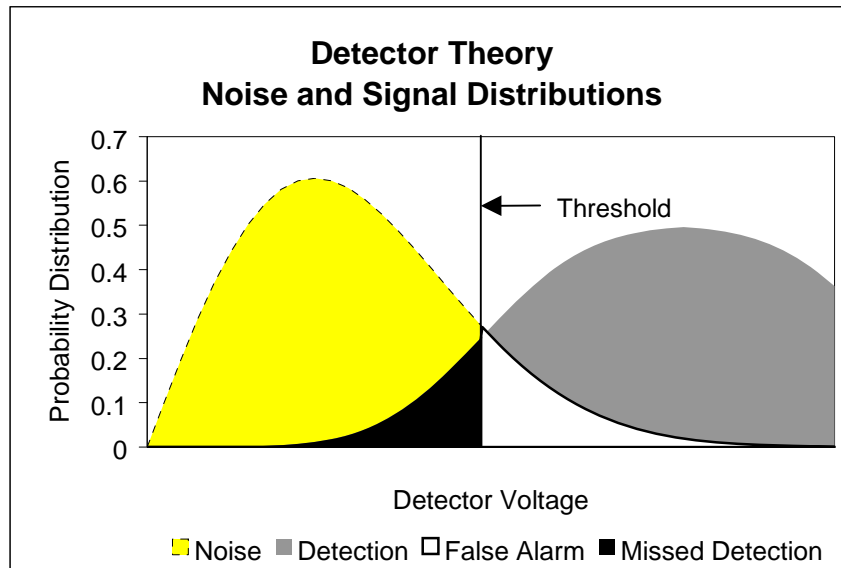
In addition, any feature related to the wheels, such as a flat spot, will lead to features at a rate of the speed of the train divided by the circumference of the wheel. For the different steady state speeds of trains and various wheel diameters these phenomena will be in the range of about 3-15 Hz. For example, an 8-Hz rate of flat spot hitting the rail would result in an 8-Hz rate of transients at any point. A transient related to a spot on the rail may result in patterns in time proportional to the spatial relationships of the wheels and will result in phenomena that can be correlated with the distance of the train from the sensor.

## DETECTOR OPERATING CHARACTERISTICS

An acceptable method for quantitatively evaluating the performance of a binary decision system is via hypothesis testing theory or the detector operating characteristics (DOC). The figures of merit for detectors of this type are:

- 1) Probability of detection or probability of missed detection, and
- 2) Probability of false alarm.

A measure of the presence of the train is chosen with a tolerable false decision probability and detection requirement. For example it may be determined that when no train is present, the system inadvertently alerts the flagman less than once during a 10-hour day and correctly detects the presence of a train at 2 miles with a probability of at least 99%. These statements can be related to a standard probability of false alarm ( $P_{FA}$ ) and probability of detection. For example, if an independent decision is made 20 times a second for each of the 2 rails, then the requirement is not to declare 1 or more false detections out of the  $1.4e^6$  decisions or  $P_{FA}$  equals  $6.9e^{-7}$  (if 1 decision each second then  $P_{FA}$  is  $1.4e^{-5}$ ). The probability of false alarm and the probability distribution function for the chosen measure when the train is not present determine a threshold level (see *Figure 7*). The probability distribution function for the measure when the train is present at various ranges can then be utilized to evaluate the detection performance of the proposed system. Typically for situations of interest for this project, the probability of detection increases as the range decreases. The detector operating characteristics can be expressed as a performance range. A more detailed summary of



**FIGURE 7:** The noise distribution and the signal plus noise distribution with respect to an arbitrary threshold voltage.

detection theory is included in *Appendix B*.

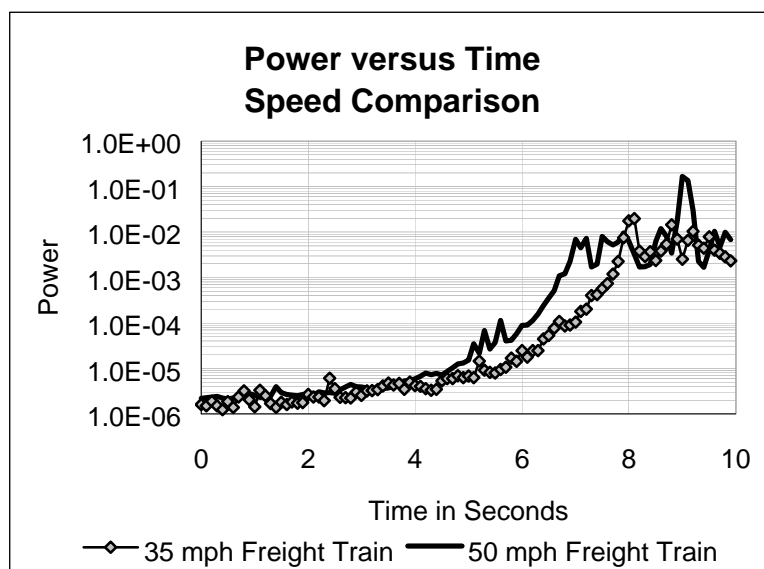
## RESULTS OF INVESTIGATION

The results of the preliminary analysis of the data were presented in the Stage 1 Final Report and are summarized here. Several characteristics observed in the vibrations of rails provide a basic understanding of how these signals can be utilized for improved safety for track maintenance gangs and track/road crossings, a more positive track of the train for improved traffic control, and to automate the pre-inspection of cars. Methods used in the preliminary analysis included power measurements of the vibrations in the rails as a function of time and the joint time and frequency analysis of the rail vibrations.

### RANGE OF DETECTION

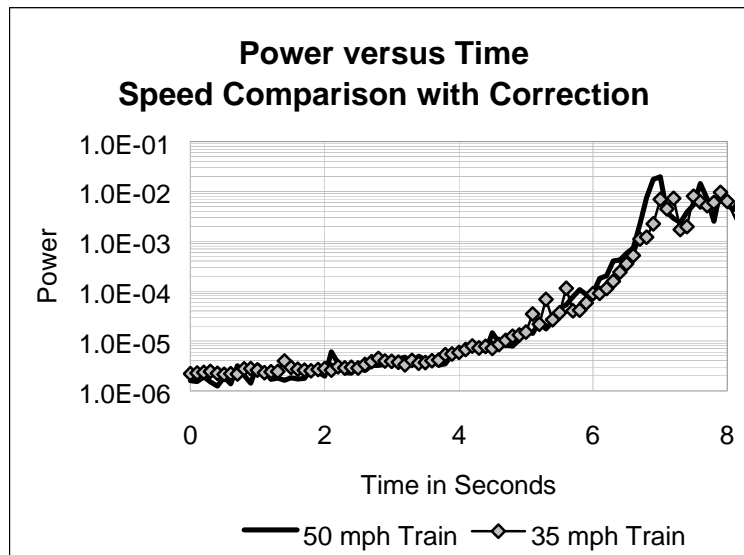
Through preliminary data analysis, the power of train induced rail vibrations, as a function of range, was determined. The results of analyzing the data for passenger, freight, and commuter trains at various speeds and at several locations showed that many factors need to be considered such as the increased detectability near a curve and the decreased detectability near an insulated joint. In general, the overall results demonstrate that the train vibrations are detectable at a range of over 3,000 feet. This range was determined from the difference in time between the initial sensor crossing by the train and the obvious increase of power above background. However, the recording system's least significant bit (LSB) in the analog to digital (A/D) converter limited the detectability during stage 1 testing. Thus, the noise level in the data was the direct result of the measuring equipment and the ambient noise level was not measured. A true range of train detection would require that a measure of the background noise level be attained.

*Figure 8* shows the power versus time as the train approaches the sensor. *Figure 9* presents the same data after correcting for the estimated train speed. From *Figure 9* it is plausible that the power is a function of the distance from the sensor. From the Stage 1 data analysis and the assumption that the power decreases exponentially with distance, an estimate of the attenuation factor was determined to be approximately 0.03 dB/ft. The trains typically induced vibrational energy of 70 dB or more above the LSB related noise floor of the recording system. *Figure 10* shows that the attenuation factor and the dynamic range of the signal level imply a detection range in excess of 2,000 feet.

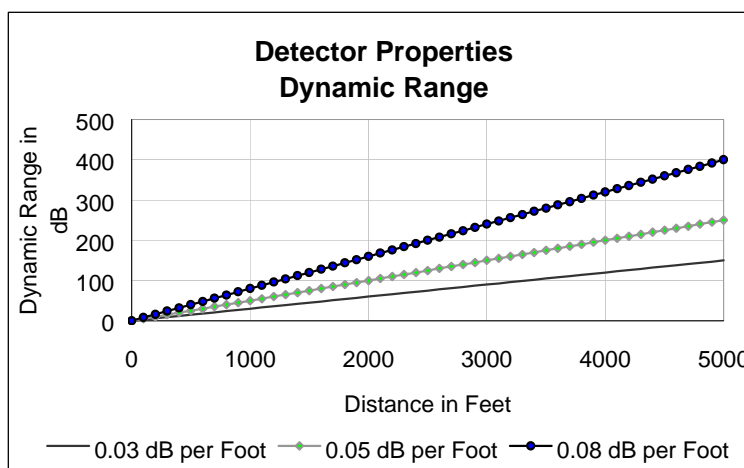


**FIGURE 8:** A power versus time comparison of two freight trains travelling at different speeds.





**FIGURE 9:** *Speed corrected data of the freight trains presented in Figure 8.*



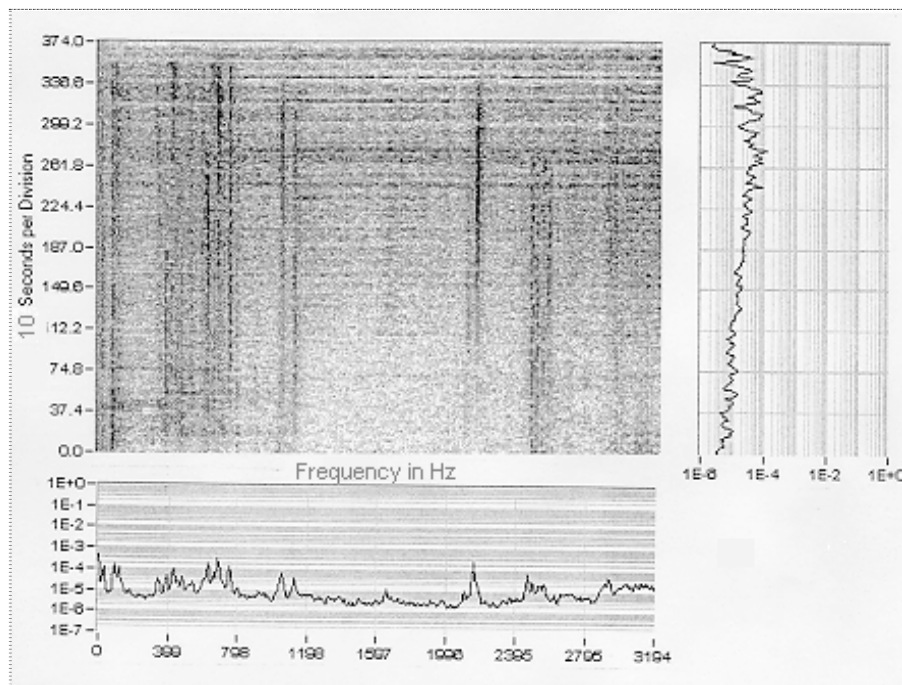
**FIGURE 10:** *Graph of the dynamic range required by a detector for detection ranges as a result of the attenuation constant in the rails.*

## TRACK RELATED EFFECTS

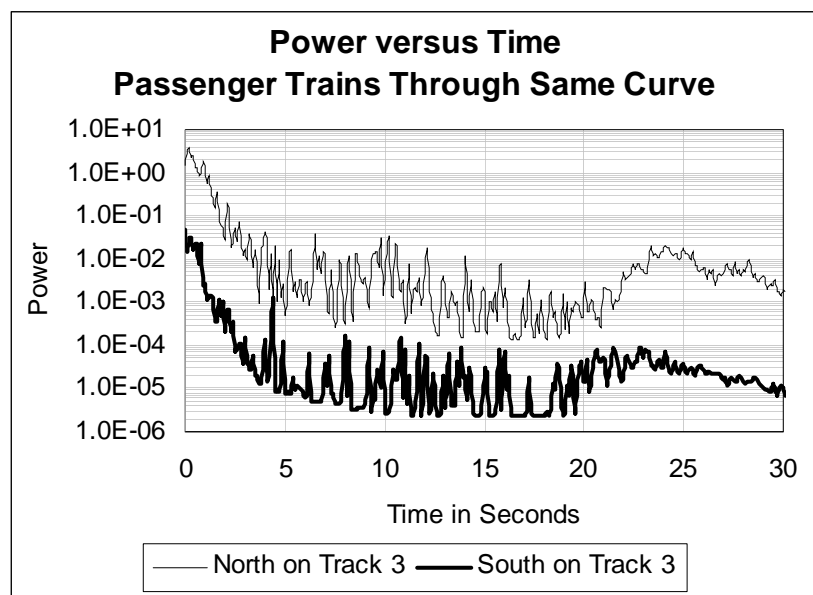
The power versus time plots were useful in determining the location of curved track and insulated joints in the rails. As the trains traveled over these, power levels increased noticeably over background. For example, as a train traversed a curve the spectrograms showed increased levels of broad band and narrow band energy (see *Figure 11*). It is believed the slipping and sliding of the wheels on the track while the train goes around the bend generates these signals. Fast passenger trains exhibited the most and strongest of these energy increases. *Figure 12* shows two examples of passenger trains on curved track. The data for the southbound train is plotted versus time after the train passed the sensors. The data for the northbound train is plotted in reverse time prior to the

train's reaching the sensor. *Figure 13* contains an example of insulated joint effects on the vibrations in rails. The power is attenuated about 15 to 25 dB at the joint. It is expected that low frequencies may be attenuated less. Both of these track related effects were useful in also estimating the direction of a train. Modulations resulting from the sleeper spacing at long distance were not yet detected, but transients related to a rail location were observed (See *Figure 11*).

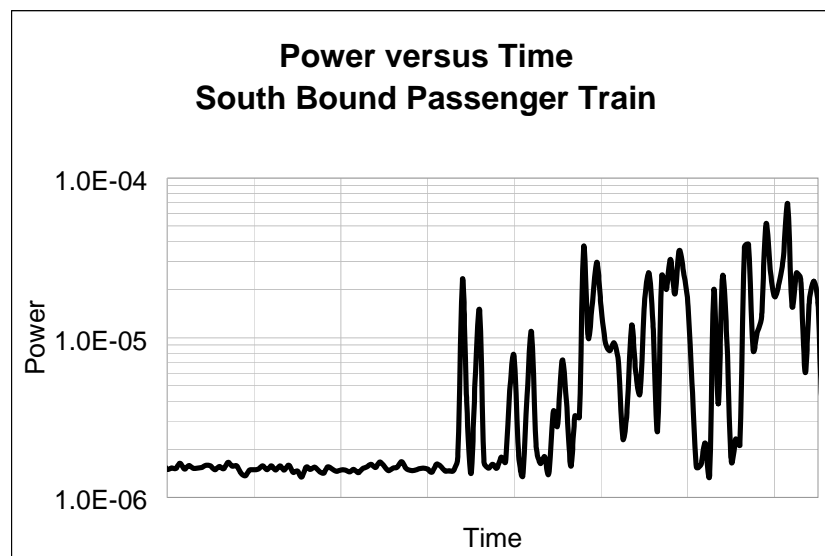
## TRAIN RELATED EFFECTS



**FIGURE 11:** Spectrogram of a freight train's vibrational characteristics as it travels around a bend.

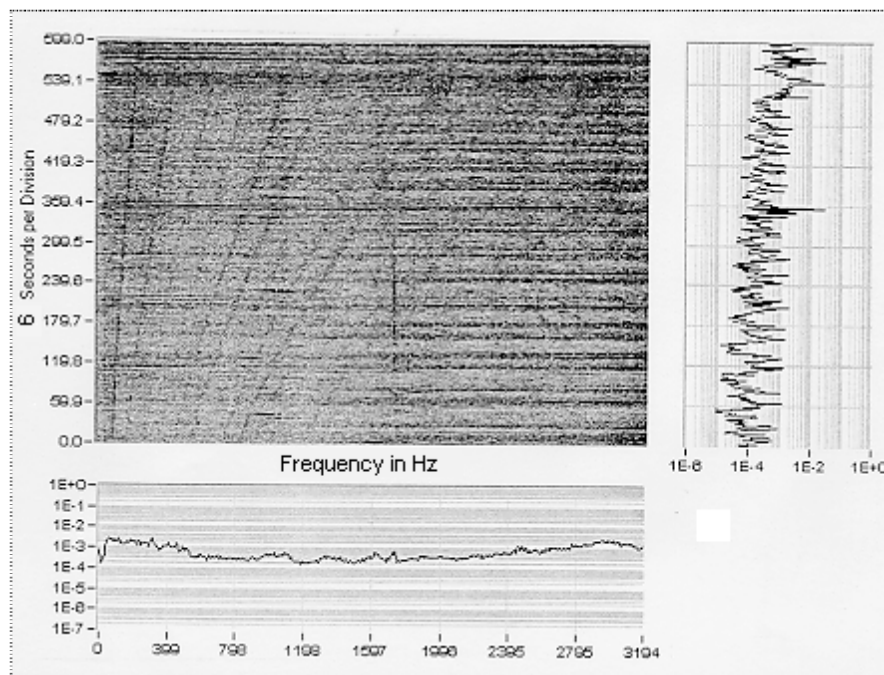


**FIGURE 12:** Two Different passenger trains of similar speeds passing through the same curve in the tracks.



**FIGURE 13:** *Power versus time of the vibrations before and after the train reaches an insulated joint.*

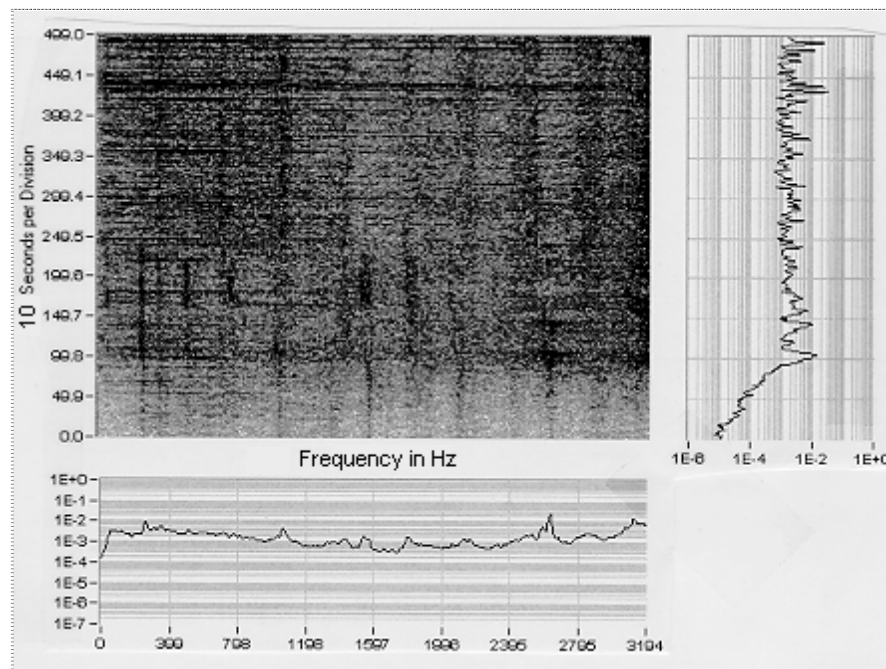
The vibrational data was also analyzed by means of joint time-frequency analysis techniques. During the acquisition of the data, a freight train slowed from its original speed and accelerated while passing over the sensors. In the spectrograms, it was seen that the narrow band energy shifted in frequency as the changes in speed occurred (see *Figure 14*). As the train slowed the frequencies decreased, and as the train accelerated, the frequencies increased. Passenger trains showed the same effect. *Figures 14 and 15* also illustrate the ability to identify the signature of individual cars. The passage of each car is associated with a definite sequence of transients and power modulation. (Notice, also, that the power increases with speed.) The cars at time mark 360 in *Figure 14* and 440 in *Figure 15* definitely exhibit a signature that is different (noisier and different spectrum). These



**FIGURE 14:** *Spectrogram of a freight train as it accelerates while on top of the sensors.*

illustrate the ability to inspect the differences in the individual cars via vibrational analysis.

## PLANS FOR IMPLEMENTATION



**FIGURE 15:** *Spectrogram of a freight train as it passes directly over the sensors.*

The feasibility of utilizing the vibrations in the rails generated by the train is becoming more realizable. Project data collection and analysis provided an overall view of this technology as an aid to flagmen, improved automobile crossings, and improved positive train control. Additional discoveries, which resulted from the analysis of the data, led to another utilization of rail vibration analysis, namely an automatic rail inspection device. Continued research and data collection is planned.

Beyond this project it is recommended that the data be further analyzed to better evaluate the potential use of this technology for the various applications identified. Based on the results of this project a working prototype of the train detector can be easily fabricated and used by railroad personnel to refine the requirements for beneficial devices. Development of the use of rail vibrations for improved positive train control should be continued. A combined on-board/off-board system may provide a very significant improvement in traffic control. In addition, more controlled testing needs to be conducted to evaluate the potential for use of rail vibrations for pre-inspecting cars. It is recommended that a controlled experiment be conducted at the Transportation Test Center in Pueblo, Colorado. At this facility the vibrational characteristics of cars with approved and then defective parts can be safely compared.

## CONCLUSIONS

During this investigation it was verified that significant and useful information could be extracted via automatic analysis of train induced rail vibrations. Although the primary goal of the project was to develop a passive device for warning maintenance gangs of approaching trains, in Stage 2 several

additional applications of the basic technology were addressed based on recommendations of railroad industry personnel:

- 1) A flagman assistance device,
- 2) Automobile crossing sensors,
- 3) Sensors for improved traffic control, and
- 4) Devices for performing automatic pre-inspections.

The first three applications make use of various levels of positive train location. It was shown during the project that the signals not only indicated the location of the train relative to the sensor but also the speed of the train. Adding this feature to the basic designs would enhance the performance for any of these three applications. Additionally it was shown that simple measures of the variability of the rail vibrations from a single sensor could be used to reliably identify cars causing high rail impact, i.e. cars in need of further inspection.

The near term potential products resulting from this study is a device to aid flagmen and a device to aid inspectors. Communications are continuing with railroad companies and the manufacturers of railroad devices to assess the potential marketability of the flagman assistance device. In addition, discussions are continuing with FRA and AAR officials regarding the need for more controlled performance evaluations of the proposed devices.

## APPENDIX A: THEORY OF RAIL VIBRATIONS

By expanding the displacement  $\eta$  in a Fourier series:

$$\eta(x, t) = \int y(k, t) e^{ikx} dk$$

$$\frac{\partial^2}{\partial t^2} y(k, t) + \gamma \frac{\partial}{\partial t} y(k, t) + \omega_0^2 y(k, t) = G(k, t)$$

where,

$$F(x, t) \equiv \int G(k, t) e^{ikx} dk$$

Thus, each wave number component obeys a damped harmonic oscillator where, unlike the classical wave equation, the natural frequency is a nonlinear function of  $k$ .

$$\omega_0^2 = (\beta + ak^4)$$

A general solution of the homogeneous equation at position  $x$  is

$$\eta(x, t) = \sum_k e^{\frac{-\gamma}{2}t} (y_+ e^{i\bar{\omega}_k t} + y_- e^{-i\bar{\omega}_k t}) e^{ikx}$$

where,

$$\bar{\omega}_k = \left[ \omega_0^2 - \left( \frac{\gamma}{2} \right)^2 \right]^{\frac{1}{2}}$$

If a general solution was assumed to be of the form:

$$\eta(x, t) = \iint \bar{y}(k, \omega) e^{ikx} e^{i\omega t} d\omega dk$$

then the special solutions of the second case correspond to modified components of the impulse function.

$$\left[ (ak^4 + \beta - \omega^2) + i\omega\gamma \right] \bar{y} = \bar{G}(k, \omega)$$

For the example  $\gamma = 0$ , then  $y_+ = y_-$  where the impulse can be represented as an initial deformation of the rail and the  $y_+(k)$  terms correspond to each of the terms in the deformation.

For the other three cases:

$$\ddot{y} + \gamma \dot{y} + \omega_0^2 y = F_0 \int e^{-ikx} f(x - vt) e^{i(k_0 x + \Omega_0 t)} dx$$

## Appendix A

$$\begin{aligned}
&= F_0 e^{i\Omega_0 t} \int e^{-i(k-k_0)x} f(x-vt) dx \\
&= F_0 e^{-i(k-k_0)vt} e^{i\Omega_0 t} \int e^{-i(k-k_0)x'} f(x') dx' \\
&= e^{i[\Omega_0 - (k-k_0)v]t} \bar{F}(k-k_0)
\end{aligned}$$

where  $\bar{F}(k)$  is the spatial Fourier transform of  $F_0(x)$ .

Thus, the components obey the forced damped harmonic oscillator equation  $(y(k, t))$  with natural frequency,  $\omega_0^2 = (\beta + ak^4)$ . If  $\Omega_0$ ,  $k_0$ , and  $v$  are zero, we retain Cases 1 and 2.

If  $\Omega_0$ ,  $k_0$ , and  $v$  are zero, then each term of the spatial forcing function oscillates at frequency,  $\omega = kv$ , which is proportional to speed. For instance, a rectangular deformation consists of components

$k = \left(\frac{2\pi}{L}\right)n$  for  $n = 1, 2, 3, \dots$  and  $L$  is a characteristic length for the deformation. The frequencies are

then harmonics of the fundamental  $f_0 = \left(\frac{v}{L}\right)$ .

Thus if the fundamental length is 3 inches and the speed is 70 mph, then the frequencies are multiples of about 350 Hz. If the train stops, all of these component frequencies decrease to dc.

If  $k_0 = 0$  and  $v = 0$ , then it is seen that oscillations (at frequency  $\Omega_0$ ) of the forcing function (the train) are impressed on each Fourier component. If the train is moving during the oscillation, each component will oscillate at  $\Omega_0 - kv$ .



## APPENDIX B: DETECTOR OPERATING CHARACTERISTICS

Consider the binary decision set of hypotheses:

$$H_0: \text{Train present} \quad \alpha \neq 0$$

$$H_1: \text{Train not present} \quad \alpha = 0$$

Where the sensor detects

$$v(t) = \alpha s(t) + n(t)$$

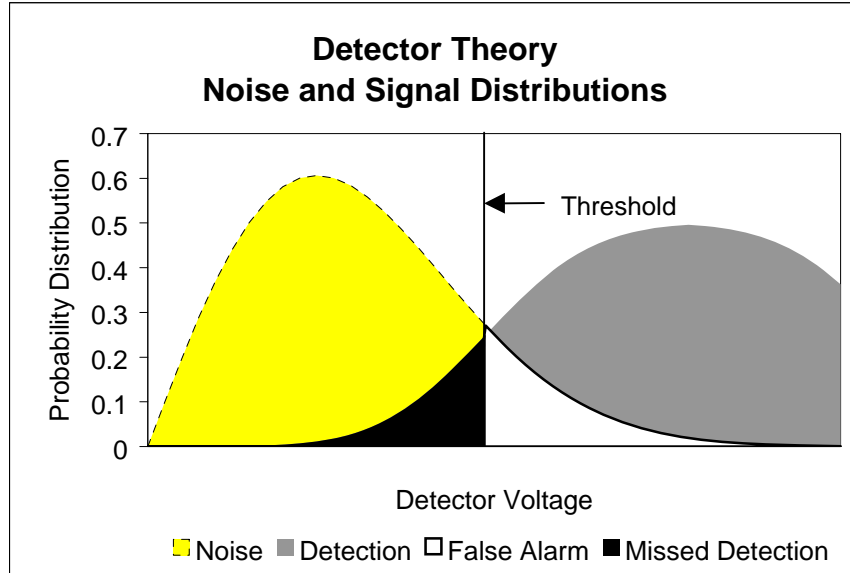
Assume the noise is the sum of white Gaussian noise.

$$\langle \bar{n} \rangle = 0$$

$$\langle \bar{n}(t) \bar{n}(t') \rangle = \sigma^2 \delta_{tt'}$$

An energy detector would use the measure derived from the likelihood ratio:

$$\lambda = \frac{1}{T} \sum_T v^2$$



From the model (or empirical data) the probability density function for  $H_1$  true and the acceptable probability of false alarm can be used to set a threshold level (see figure). The probability of detection then generally corresponds to a required value of  $\alpha$ . Various standard techniques can be employed if necessary to allow for practical aspects such as unknown  $\sigma^2$ .

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