DEVELOPMENT OF SEISMIC RISK ASSESSMENT METHODOLOGY FOR HIGH SPEED RAILWAYS

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Abstract: Methodologies for assessing the seismic risk of a high speed railway system were limited to analysis of fragilities of structures and vibration dynamics of vehicles in the past. A deterministic or scenario based approach assuming a particular devastating earthquake was also used in some methodologies. A seismic risk assessment methodology that can estimate the risk of derailment caused by earthquake is proposed in this study. Among constituent factors, the effectiveness of the seismic early warning system that detects the occurrence of earthquakes before the strong ground motion reaches the line is concerned. This study addresses a formulated method to quantify cost-benefit tradeoffs between gain in safety and false alarms. In addition, an assessment model of consequences in terms of injuries and fatalities in derailment disaster, an approach method for network of Shinkansen, and a graphical user interface are considered as perspective studies.

Key Words: seismic risk assessment, high speed railway, seismic early warning system

1. INTRODUCTION

Since Japan sits atop the junction of the Pacific, Eurasian and Philippine tectonic plates and has accordingly suffered the devastation of major earthquakes throughout its history, the seismic risk is an important consideration among the overall safety issues for the nationwide railway network, especially the Shinkansen system. Methodologies for assessing the seismic risk of a high speed railway system were limited to analysis of fragilities of structures and vibration dynamics of vehicles in the past. A deterministic or scenario based approach assuming a particular devastating earthquake was also used in some methodologies. However, it is important to take a continuous network system of the Shinkansen into consideration for the estimation of the total seismic risk. Therefore, a seismic risk assessment system (SRAS) has been developed for the entire railway network of the Shinkansen in all possible earthquake scenarios.

For the protection of the Shinkansen system against earthquakes, a seismic early warning system (SEWS) is being operated that automatically induces trains to stop when a potentially destructive earthquake is detected at an accelerometer located near the epicenter. As many other warning systems, one of the major managerial concerns of SEWS is to find the optimal trade-off between gain in safety and the costs associated with false alarms issued by the system. In order to address this target, this study develops a procedure for seismic risk
analysis tailored to the Tohoku Shinkansen focusing on the effectiveness of the existing SEWS and of alternatives to it.

The procedure of the ARAS includes the standard method of earthquake hazard analysis (identification of seismic sources, estimation of recurrence parameters and specification of attenuation model). It also includes the special features for the seismic risk analysis of railway systems such as the spatially distributed nature of the system, the seismic behavior of running trains and track structures, relationship among earthquake magnitudes, epicentral locations, the activation/non-activation patterns of the warning systems, and the probability that a train at a given location derails. In addition, it considers consequences in terms of the number of injuries caused by the earthquake disaster.

2. THE CURRENT SEWS OF THE TOHOKU SHINKANSEN

The Tohoku Shinkansen is a high-speed railway along the eastern side of Honshu, the largest of the Japanese islands, operated by East Japan Railway, one of the railway companies that emerged from the privatization of the previous Japanese National Railways. The line is about 500 km long and links Tokyo to the northern city Morioka with 16 intermediate stations.

The structure of the Shinkansen line is comprised of continuous double-track viaducts, except for tunnels in mountainous parts of the line, while the most conventional railway lines do of embankments in Japan. Accelerometers are installed at 11 coastal seismic stations and 24 wayside seismic stations. The locations of coastal stations are chosen to provide the longest lead time for trains to stop safely for offshore earthquakes. Therefore, as the intensity of ground motion at a coastal station exceeds the chosen threshold level, emergency braking is automatically activated for all trains running in the corresponding track segment.

The wayside system consists of 24 accelerometers installed at nearly equal intervals between Tokyo and Morioka, and each wayside accelerometer is corresponding to one of 24 non-overlapping operational track segments. They operate for protect against inland earthquakes and also as a second line of defense against offshore earthquakes that might not be triggered by the coastal stations. Furthermore, the intensity of ground motion recorded at a wayside station is the basis for operational decisions.

After an earthquake triggered emergency train braking, operational actions to be taken vary depending on the intensity of the ground motion recorded at a wayside station. Train operation is to be resumed as soon as the intensity of the ground motion at a wayside station is proved to be so small that there is obviously no need of post-earthquake track inspection. In this case, only a short delay, typically several minutes, will be caused to the train operation. Otherwise, a post-earthquake inspection will be made either quickly by on-board or more carefully by on foot depending on the intensity of the ground motion. These cases can cause longer delays to the train schedule, typically around a couple of hours in the former case and several hours in the latter case.

Both coastal and wayside stations can trigger emergency braking based on strength of P waves and S waves. The obvious advantage of using P waves is increase in lead time of emergency braking. This benefit is counterbalanced by increase in the rate of false alarms to some degree due to the limited accuracy of P wave based detection.
3. MODELING THE SYSTEM

3.1. Seismic Environment

Japan is a very earthquake–prone country. Figure 1 shows the occurrence of earthquakes in and around Japan. As this figure shows, there are differences in the seismicity depending on the region. The areas along the JR East Shinkansen lines are the greatest seismicity bands of the Pacific coast.

A statistical analysis of the historical data produces estimates of a rate of earthquakes. The rate, \( \lambda(M) \) is given in events/year of magnitude larger than \( M \) in a seismogenic source. We assume that \( \lambda(M) \) follows the Gutenberg-Richter relationship:

\[
\log_{10} N(M) = a - b M, \quad M < M_{\text{max}}
\]

where \( a, b \) and \( M_{\text{max}} \) are constants characterizing each seismogenic source.

The ARAS uses a "seismicity model" that bases on earthquake observation record data such as Figure 1 and Equation (1) to estimate the frequency of the maximum to minimum earthquakes that are predicted for each hypocenter area. The seismicity model consists of three submodels: A planar hypocenter model used for gigantic earthquakes that occur along plate boundaries; a linear hypocenter model used for active faults; and a random earthquake area hypocenter model used for seismicity within plates that are neither gigantic earthquakes caused by plate boundaries nor active faults. These represent seismicity by the hypocenter location coordinates, magnitudes and frequency for more than 45,000 earthquake scenarios that cover all of Japan.

![Figure 1: Earthquake epicenters in and around Japan](image-url)
3.2. Strong Motion Attenuation
Several studies of strong motion attenuation have been made using data from the region of interest and from other seismically active areas of the world. For our analysis, we are interested in the attenuations of peak ground acceleration (PGA) and spectral intensity (SI). Molas et al. (1995) derived attenuation relationships for both PGA and SI based on a large number of data obtained in Japan by reliable devices. The formula of strong motion attenuation is stated as:

\[
\log y = b_0 + b_1 M + b_2 r + b_3 \log r + b_4 h + c_i \pm \sigma p
\]  

where \( y \) is the intensity measure (either PGA or SI), \( M \) is magnitude of an earthquake, \( r \) is hypocentral distance (km), \( h \) is hypocentral depth (km), \( b_0, b_1, b_2, b_3 \) and \( b_4 \) are regression coefficients, \( c_i \) is a constant of locality, \( \sigma \) is the standard deviation of regression errors and \( p \) is a parameter to represent confidence interval of the estimate. Table 1 shows the values of these coefficients.

<table>
<thead>
<tr>
<th></th>
<th>( b_0 )</th>
<th>( b_1 )</th>
<th>( b_2 )</th>
<th>( b_3 )</th>
<th>( b_4 )</th>
<th>( c_i )</th>
<th>( \sigma )</th>
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</thead>
<tbody>
<tr>
<td>PGA (cm/s²)</td>
<td>0.206</td>
<td>0.477</td>
<td>-0.00144</td>
<td>-1.00</td>
<td>0.00311</td>
<td>0.225</td>
<td>0.276</td>
</tr>
<tr>
<td>SI (cm/s )</td>
<td>-1.64</td>
<td>0.614</td>
<td>-0.00133</td>
<td>-1.00</td>
<td>0.00233</td>
<td>0.184</td>
<td>0.257</td>
</tr>
</tbody>
</table>

3.3. Configurations of SEWS
To find the optimal trade-off between gain in safety and costs associated with false alarms, we consider the following configurations of SEWS configuration and evaluate their effectiveness.

**System A** This system is a baseline in comparison with which we examine the effectiveness of other alternative systems. System A is modeled as a warning system which is composed of only the wayside part of the current SEWS. This system operates on S waves and triggers automatic braking for trains on a operational track segment when PGA recorded by the corresponding wayside accelerometer exceeds a threshold value, which is set at 40gals.

**System B** This system had been in operation until 1999. It assigns each track segment to some of the 11 coastal accelerometers in addition to the wayside system configuration of system A. These 11 preset sections, hereafter referred as "shut-down" sections, cover the entire line with some overlap. Each shut-down section is composed of neighboring operational track segments. The controlling policy of the coastal warning of this system is that when the earthquake motion at a coastal accelerometer exceeds a preset intensity, then automatic braking is issued for all trains in the corresponding shut-down section. This system operates on S waves and the threshold value of PGA for triggering automatic braking is set at 40gals for both wayside and coastal accelerometers.

**System C** The underlying idea of system C is that it is able to issue warnings with increased lead time for emergency braking if the system can operate on P waves in addition to S waves. Another concept of this system is that the estimated magnitude of the earthquake \( M \) and the epicentral location \( x \) determine the area of the track section to be shutdown. This is the UrEDAS: see Nakamura (1999). The UrEDAS evaluates the destructive potential at all locations \( s \) along the track based on the estimation of \( M \) and \( x \) of the earthquake and historical data on damage and non-damage events depending on \( M \) and
epicentral distance \(d(x,s)\). Emergency braking may or may not be ordered depending on the first estimate of \(M\) and \(x\) from a single station using P waves and the procedure is then repeated using S waves with increased accuracy of the estimation.

**System D** This system corresponds to the system that is currently in operation on the Tohoku Shinkansen. This system maintains the geographic configuration of the coastal accelerometers and controlling policy of system B, but its coastal system operates on not only S waves but also P waves as in system C. The current system on the Tohoku Shinkansen is called the "Compact" UrEDAS as it is a truncated version of the UrEDAS. Although the details of the method to evaluate the destructive potential of the earthquake used in the Compact UrEDAS are different from those in the UrEDAS, we regard them as identical in this study for simplicity.

In addition to the above-mentioned different system configurations of SEWS, we examine the effect of changing earthquake intensity parameters at wayside stations from PGA to SI. Since SI takes response spectra of structures into consideration, it is far better as a measure of the destructiveness of earthquake motion than PGA.

### 3.4. Occurrence Rate of Risk Events

In order to avoid derailments, the present SEWS tends to stop trains at a high rate. In a few cases such actions may indeed result in derailment avoidance, but in most cases they produce "false alarms" and unnecessary delays of various durations. Hence, a reasonable way to characterize the performance of the SEWS is to calculate the rate of derailments the were not prevented and the rate of delays of various magnitudes, more specifically, we define four rates:

- \(\mu(D)\) : annual rate of earthquake-induced *derailments*. This is the expected number of trains per year that derail due to earthquakes, anywhere along the line.
- \(\mu(S)\) : annual rate of earthquake-induced *short delays*. This is the expected number of trains per year that, after being stopped by the SEWS, are immediately allowed to resume operation without any inspection of the tracks.
- \(\mu(M)\) : annual rate of earthquake-induced *medium delays*. This is the expected number of trains per year that, after being stopped by the SEWS, resume operation at low speed to perform on board inspection of the track.
- \(\mu(L)\) : annual rate of earthquake-induced *long delays*. This is the expected number of trains per year that, after being stopped by the SEWS, are not allowed to resume operation until on-foot inspection of the tracks has been completed.

The general procedure to calculate the rates of the events \(\varepsilon\) of interest (\(\varepsilon\) is \(D, S, M,\) or \(L\), where the symbols respectively stand for derailment, short delay, medium delay, and long delay events) under the given warning system \(W\) (where the symbols respectively stand for System A, B, C and D), \(\mu(\varepsilon|W)\) is given by:

\[
\mu(\varepsilon|W) = \int_{M} \int_{x} \sum_{s} \lambda(M,x)E(n_{s})P(\varepsilon|M,x,s,W)dxdm
\]

where

- \(\lambda(M,x)\) is the rate density per year of earthquakes of magnitude \(M\) at epicentral location \(x\). This density is given by Equation (1).
- \(E(n_{s})\) is the expected number of trains running at a random point in time in operational
segment $s$.

$P(e|M,x,s,W)$ is the probability of event $e$ occurring under the given SEWS for a train running in operational segment $s$, an earthquake of magnitude $M$ and epicentral location $x$. This probability may in turn be written as:

$$ P(e|M,x,s,W) = \sum_{T} P(e|M,x,s,T)P(T|M,x,s,W) $$

where $T$ is the generic trigger/no-trigger status of SEWS. $T$ has the following logical values: $T=T_{c}$ for automatic braking triggered by coastal system, $T=T_{w}$ for automatic braking triggered by wayside system, and $T=T_{0}$ in the case of no trigger.

4. RISK ANALYSIS

Here we show how the probabilities of various events in the right hand side of Equation (4) are evaluated for different $e$, $T$ and $W$.

4.1. Conditional Probability of Trigger, $P(T|M,x,s,W)$

System A

For System A, there is one-on-one correspondence between an operational track segment and a wayside accelerometer and no coastal system is installed. Therefore, automatic emergency braking occurs for an operational track segment when the intensity of the earthquake recorded at the designated wayside accelerometer exceeds the preset threshold value. Trigger probability for system A is obtained as:

$$ P(T_{c}|M,x,s,A) = P\left(y_{w}(M,r(x,s)) \geq Y_{w}^{*}\right) $$

where $r(x,s)$ is the distance between $x$ and $s$ and $y_{w}(M,r(x,s))$ is the attenuated intensity of an earthquake of magnitude $M$ at the operational track segment $s$ and $Y_{w}^{*}$ is the trigger threshold for a wayside accelerometer. The coastal accelerometers are not used in this system. Therefore:

$$ P(T_{c}|M,x,s,A) = 0 $$

and the probability of no trigger is:

$$ P(T_{0}|M,x,s,A) = 1 - P(T_{c}|M,x,s,A) $$

System B

For system B, if designated coastal and wayside accelerometers record the levels of the earthquake intensity that exceed the preset threshold value, they issue emergency braking. Only the first issue is actually effective. The probability of coastal trigger $T_{c}$ is given as:

$$ P(T_{c}|M,x,s,B) = \left\{ \begin{array}{ll}
P(y_{c}(M,r(x,i)) \geq Y_{c}^{*}); & (r(x,s) \geq r(x,i)) \\
(1 - P(y_{w}(M,r(x,s)) \geq Y_{w}^{*}))P(y_{c}(M,r(x,i)) \geq Y_{c}^{*}); & (r(x,s) < r(x,i)) 
\end{array} \right. $$

where $y_{c}(M,r(x,i))$ is the attenuated intensity of an earthquake of magnitude $M$ at coastal station $i$ and $Y_{c}^{*}$ is the trigger threshold for a coastal accelerometer. The probability of
wayside trigger $T_w$ is given as:

$$P(T_w|M,x,s,B) = \begin{cases} 0 & \frac{P(y_w(M,r(x,s)) \geq Y^*_w)}{(1 - P(y_v(M,r(x,i)) \geq Y^*_v))P(y_w(M,r(x,s)) \geq Y^*_w)} \ ; \ (r(x,s) < r(x,i)) \\ 1 & (r(x,s) \geq r(x,i)) \end{cases}$$

(9)

And the probability of no-trigger $T_0$ is given as:

$$P(T_0|M,x,s,B) = (1 - P(y_v(M,r(x,i)) \geq Y^*_v))(1 - P(y_w(M,r(x,s)) \geq Y^*_w))$$

(10)

**System C**

System C may trigger upon the arrival of either P or S waves to the coastal stations. For given estimates of $M$ and $\Delta$, the system causes trains to stop if the parameter $y$ given as below is larger than the preset threshold value $Y^*$.

$$y = 0.71\hat{M} - \log_{10}\hat{\Delta}(x,i)$$

(11)

where $\hat{M}$, $\hat{\Delta}(x,i)$ are estimated magnitude and epicentral distance by the UrEDAS. Considering uncertainty on the estimates of $(M,x)$, $y$ may be modeled as a random variable with normal distribution, mean value given by Equation (9) and variance,

$$\sigma_y^2 = (0.71\sigma_M)^2 + \left\{ \log \left( \frac{\sigma_\Delta}{\Delta} \right) \right\}^2$$

(12)

Based on the data about empirical performance of the UrEDAS, we consider the following as reasonable values for the standard deviation of the estimation error for earthquake magnitude and epicentral distance from P wave arrival and those from S wave arrival.

$$\sigma_{M,p} = 1.0 \quad \sigma_{\Delta,p} = 0.5\Delta$$

(13)

$$\sigma_{M,s} = 0.5 \quad \sigma_{\Delta,s} = 0.25\Delta$$

(14)

For system C, the probability that a coastal station triggers on the arrival of P waves is given as:

$$P(T_{c,p}|M,x,s,B) = P(y_p \geq Y^*)$$

(15)

and the probability that a coastal station triggers on the arrival of S waves is given as:

$$P(T_{c,s}|M,x,s,B) = (1 - P(y_p \geq Y^*))P(y_s \geq Y^*)$$

(16)

where $y_p$ and $y_s$ are estimated value of $y$ based on P waves and S waves, respectively. Also, the probability of no-trigger at a coastal station is given as:

$$P(T_{0,c}|M,x,s,B) = (1 - P(y_p \geq Y^*)) (1 - P(y_s \geq Y^*))$$

(17)

Considering that each track segment along the line can be triggered by all coastal stations in the case of system C, the probability that $k$-th ($k = 1,2,\ldots$) arrival of P or S waves to any of
coastal stations triggers the emergency braking of trains along the track segment $s$ is given as:

$$P(T|M, x, s, C) = P(y(k, x, M) \geq Y'(k, s)) \prod_{i=1}^{s} (1 - P(y(i, x, M) \geq Y'(i, s)))$$  \hspace{1cm} (18)

**System D**

For system D, which is a truncated version of system C, the probabilities of various $T$ are given also by Equation (8),(9) and (10).

### 4.2. Seismic Fragility of the Viaduct Structure

If a train runs through damaged track, it may likely derail. In order to understand the probability of derailment caused by facility damage, numerical simulations were conducted using some historic ground motions scaled to produce 19 set values of $SI$ ($SI = 10, 15, 20, ..., 100$ Kine). These motions were applied to structures with different periods. Six types of viaducts were selected as numerical viaduct models, and four damage levels were considered. Assuming that the distribution of the occurrence of damage is normal distribution, the fragility curve of viaduct was calculated; see Figure 2.

The viaduct structure of the Shinkansen is composed of a series of short spans whose length $SP$ is about 7m. Assuming the number of continuously damaged or continuously undamaged spans of the viaduct has a geometric (essentially exponential) distribution, the relation between the mean number of continuously undamaged spans $n_0(y)$ and the probability $P_d(y)$ that a building being damaged, given that the local level of earthquake intensity is $y$ as follows, see Papadimitriou (1995):

$$n_0(y) = \frac{1 - P_d(y)}{P_d(y)}$$  \hspace{1cm} (19)

### 4.3. Probability of Derailment Caused by Damaged Viaduct

We assume that the intensity of an earthquake at the track reaches its maximum value instantly and that a train of length $L$ travels a distance $LE$ after the arrival of the S waves. We define the probability of derailment $P_d$ as the probability that the train meets damaged track
(note that derailment due to vibratory motion without structural damage is excluded). Under these simplifying assumptions, the event of no-derailment occurs only if the last point of the train, coming from undamaged conditions (before the strong vibratory motion arrives at the track), encounter no damage in track length $LE$ and stops instantly, and if the instant before stopping, the section of track of length $L$ occupied by the train is entirely undamaged given that it is undamaged at the location where the train terminates. From the fact that the distribution of undamaged and damaged section is exponential, the probability of no-derailment given $y$ is given by:

$$P(ND|y) = e^{-[(LE+L)/(SP)]/n_y(y)}$$

(20)

Therefore, taking complimentary probability, the probability of derailment is given as:

$$P(D|y) = 1 - P(ND|y) = 1 - e^{-[(LE+L)/(SP)]/n_y(y)}$$

(21)

Taking the expectation of Equation (21), the probability of derailment, $P_d(M,x,s)$ of a train running is operational segment $s$, given the occurrence of an earthquake of magnitude $M$ at epicentral location $x$ is given by:

$$P_d(M,x,s) = 1 - E_{[M,x,s]}[e^{-[(LE+L)/(SP)]/n_y(y)}]$$

(22)

In Equation (22), $LE$ is the length of track that a train in operational segment $s$ covers and has the following values depending on whether or not of the occurrence of emergency braking from the coastal station. When emergency braking is ordered, $LE$ is equal to $D_{stop} = \frac{v_0^2}{2a_e}$, where $v_0$ is the speed of the train when braking starts and $a_e$ is the deceleration of the emergency braking. If not for the occurrence of emergency braking, $LE$ is equal to $SEC(s)$, the half of the average distance between trains in $s$ in the same direction. Therefore:

$$P(D|M,x,s,T_{c,w}) = 1 - E_{[M,x,s]}[e^{-[(D_{stop}+L)/(SP)]/n_y(y)}]$$

(23)

$$P(D|M,x,s,T_0) = 1 - E_{[M,x,s]}[e^{-[(SEC(s)+L)/(SP)]/n_y(y)}]$$

(24)

**4.4. Probability of Various Delays**

Delays can be caused by either the coastal or the wayside system; these events are denoted by $T_c$ and $T_w$ as indicated earlier. Here we give formulas for just the former, for the reasons of brevity. The equations are completely analogous for an $T_w$ based operation.

$$P(S|M,x,s,W) = P[y(M,\Delta(x,s)) \leq Y_{imp1}]$$

(25)

$$P(M|M,x,s,W) = P[Y_{imp1} \leq y(M,\Delta(x,s)) \leq Y_{imp2}]$$

(26)

$$P(E|M,x,s,W) = P[Y_{imp2} \leq y(M,\Delta(x,s))]$$

(27)
where $Y_{\text{insp1}}$ and $Y_{\text{insp2}}$ are the threshold intensity for on board inspection and on foot inspection, respectively.

4.5. The Probability of Derailment Caused by Seismic Vibration

In order to evaluate the probability of derailment due to seismic vibration, a numerical simulation model of a train was used. Derailment was assumed to occur if the wheel moves more than 70mm relative to the rails during the motion of the train depends on the dynamic characteristics of the supporting structure. For viaducts, the fundamental period ($T_{eq}$) varies from 0.3 to 1.5, and the damping was set to 0.05. Eleven recorded earthquake motions were scaled to produce 19 set values of SI ($SI = 10, 15, 20\ldots100$ Kine). These motions were applied to structures with different periods. Assuming that the distribution of the train-rail displacement is normal distribution, the probability of exceeding 70 mm of relative motion was calculated; see Figure 3.

![Figure 3](image)

Figure 3 The probability of derailment caused by seismic vibration as a function of SI value for different natural periods of the supporting viaduct

5. RISK RESULTS

We calculated the rate of the four risk events: derailment $\mu(D)$, short delay $\mu(S)$, medium delay $\mu(M)$ and long delay $\mu(L)$ for the four SEWS configurations: system A, system B, system C, system D and a modified system D, in which SI is chosen as the wayside intensity parameter instead of PGA. We calculated Equation (3) with the setting of $M$ at the interval of 0.1 and $x$ into 194 discrete point sources. $M$ and $x$ are included in the “seismicity model” (see 3.1). Given $s$, an operational segment that equals to a position of a potential train, and $E(ns)$, the expected number of trains on the position that can be obtained by a real train time table of the Shinkansen, probabilities in Equation (3) can be solved. The results of the comparison between four alternatives in terms of the rate of events are given in Table 2. Our main findings on the effectiveness of these systems are as follows:

- **Coastal station** The reduction of $\mu(D)$ caused by coastal stations in system B compared with system A, which has no coastal stations, is by about 5%. The coastal system has no effect on the rates of medium and long delays, because they are controlled by the wayside system. On the other hand, the coastal system is the primary cause of false alarms, whose rate depends on the level of ground motion at which trains are stopped.

- **P wave detection** The additional reduction of $\mu(D)$ caused by coastal stations in system D, which can operate on P waves, compared with system B, which operates only on S waves,
is small. On the other hand, it causes about three times as many short delays as the coastal system B does in its original setting $Y_c^* = Y_w^* = 40$ gals.

**Triggering policy** The additional reduction of $\mu(D)$ caused by coastal stations in system C, in which any of the coastal accelerometer can order emergency braking of trains anywhere along the track, compared with system D, in which emergency braking is ordered only to the designated shut-down section of a coastal accelerometer, is also very modest. On the other hand, it causes about twice as many short delays as the coastal system D does.

**Alternative measures of seismic intensity** There is a great advantage in changing the intensity parameter of the wayside system of the current SEWS from PGA to SI. As is designated as system D(SI) in Table 2, it can reduce the rate of long and medium delays at least in half without increasing the rate of derailments.

From these results, it is clear that triggering at the coastal stations is effective to reduce $\mu(D)$. Operating on P waves is potentially effective to reduce $\mu(D)$. It should be considered to select an appropriate triggering policy to increase the effectiveness. Although the use of the coastal accelerometers and the P wave information can reduce $\mu(D)$, it increases $\mu(S)$ because of the less accuracy of estimation of earthquake intensity. $\mu(M)$ and $\mu(L)$ can be reduced using SI instead of PGA, because SI correlates more closely with the destructiveness of earthquake motion than PGA.

<table>
<thead>
<tr>
<th>System</th>
<th>$\mu(D)$</th>
<th>$\mu(S)$</th>
<th>$\mu(M)$</th>
<th>$\mu(L)$</th>
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<tr>
<td>A</td>
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<td>B</td>
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<tr>
<td>C</td>
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</tr>
<tr>
<td>D</td>
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<td>D(SI)</td>
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6. **PERSPECTIVE STUDY PROGRESS**

In order to realize more realistic and precise analysis, two phase approaches have been implied in this study; one is the development of a consequence model, the other is a Regional Approach.

6.1. **Consequence Model**

In order to make effective investments in countermeasures for the earthquake disaster, the estimation of the consequences is of great importance. Using real derailment data set, the effects on the number of minor injuries, serious injuries, and fatalities of various conditions at the time of derailment as well as the occurrence of secondary accidents such as turnover, train falling or intrusion are quantified. Then, the consequence model to estimate the number of casualties and fatalities in the cases of derailment is developed, as shown in Figure 4.
6.2. Regional Approach
In real train operation, there are many trains in the Shinkansen network during operating time, and conditions vary along the track. In this situation, multiple accidents including head-on collision may occur in different segments, and the probability of derailment is different for each condition. To analyze the simultaneous derailment risk for the whole Shinkansen network, we have developed a regional risk analysis approach for the derailment of high speed trains. In the program that implements the regional approach, the actual timetable and track conditions of the Shinkansen line are used, and possible post-derailment scenarios are considered. Figure 5 shows an event tree that includes these possible scenarios. Not only the probability of derailment but also the consequences of derailment events is also taken into account.
6.3. Graphical User Interface

In order to efficiently calculate the earthquake impact assessment for the Shinkansen above and display the results in an easy-to-understand manner, we configured the system as an application program that uses a graphical user interface. Figure 6 shows an example of the display screen used for scenario analysis. By selecting an item in this list, the hypocenter location and magnitude of the earthquake being evaluated can be selected. Figure 7 shows the risk analysis results screen. The point location of the selected track section range is shown in the horizontal axis, and the expected frequency for each risk phenomenon is shown as a line graph. This will allow comparison of the frequency by sections and risk phenomena.
7. CONCLUSIONS

In this study, the quantitative analysis for the effectiveness of various configurations of the SEWS for the Tohoku Shinkansen is proposed. The results of the analysis obtain as follows:

1. Triggering at the coastal stations is effective to reduce the probability of derailment. Operating on P waves is potentially effective to reduce the probability, while it should be considered to select an appropriate triggering policy to increase the effectiveness.
2. The use of the coastal accelerometers and the P wave information increases the probability of short delay because of the less accuracy of the estimation of the earthquake intensity.
3. The probabilities of medium and long delays can be reduced using SI instead of PGA, because SI correlates more closely with the destructiveness of earthquake motion than PGA.

In addition, as perspective studies, the development of the consequence model, the regional approach, and the graphical user interface are in progress.

REFERENCES