Regional Seismic Risk of Railway System Including Derailment Consequences

by

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Submitted to the Department of Civil and Environmental Engineering
In Partial Fulfillment of Requirements for the Degree of

Master of Science In Civil and Environmental Engineering

at the
Massachusetts Institute of Technology

September 2006

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ABSTRACT

To evaluate the seismic risk of railway networks, a derailment consequence model and a regional approach are developed.

The consequence model estimates the casualty and fatality rates for passengers as a function of train speed and includes two sub-models. The first sub-model, which is for the case when the train remains in its own track after derailment, was developed using historical accident data. The casualty and fatality rates are estimated using a linear logistic model. The other sub-model, for the case of head-on collision and train fall, was developed using numerical simulation results by the U.S.DOT.

The regional approach estimates earthquake risk for the entire network. In the approach, first, the probabilities of possible derailment scenarios including head-on collision cases are calculated. To calculate the probabilities of derailment due to seismic vibration and facility damage, the derailment probability model is applied. After one scenario is selected by Monte Carlo method based on calculated probabilities, the consequences are calculated for the scenario applying the consequence model developed previously. Through an application to the Tohoku Shinkansen line, we illustrate how the system is in many ways an improvement over the current JR East system.

Thesis Supervisor: Daniele Veneziano
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Acknowledgements

The completion of this thesis would not have been possible without the help of many people.

First and foremost, I would like to present my deep and sincere gratitude to my research advisor, Professor Daniele Veneziano. He has reminded me to pursue truth through academic thinking. Professor Veneziano also taught me how to reach the goals that I set for this research project. I am confident that the knowledge and experience I gained will help my career in the future.

I cannot thank Professor Joseph Sussman enough for all of the help he has given me at MIT. He has encouraged and guided me throughout my years there. In addition, I understand that without his dedicated help, we could not have paved the way to a longstanding relationship between MIT and JR East. I am looking forward to working with him in the future to keep up this excellent relationship.

I would like to extend my appreciation to the East Japan Railway Company (JR East), who has provided me with funding and time to get the opportunity to pursue this achievement. I also wish to thank the many colleagues in the U.S. and in Japan who have helped in my work and life at MIT. Though what I have learned there, I will be able to maintain the highest level of service at JR East.

I would like to extend my sincere thanks to Lucile M. Guillaud. Her eagerness to work and kindness without discrimination is the driving force behind our project.

I would also like to thank Melanie Howell. I appreciate her understanding of the many structural and social-based differences between English and Japanese.

Thanks to all my friends who I met in Greater Boston. Your friendship made my student life very enjoyable.

Finally, I would like to thank my husband, Keiichi Uchiyama, my parents, Teruo and Teruko Misu, and my brother Kentaro Misu, for their wonderful support my endeavors and patience while waiting for my return to Japan.

This research has been funded by East Japan Railway Company as a cooperative research project with MIT.

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1 Introduction

Japan is a very earthquake-prone country. More than 100 earthquakes of magnitude larger than 4[1] occur on average every month in 2005. The number of earthquakes occurring each month in 2005 is shown in Table 1-1.

Table 1-1: Number of Earthquakes in Japan in the year 2005 (archives of the Meteorological Agency in Japan)

	Jan	Feb	Mar	Arp	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
M4～	100	70	98	76	76	87	115	112	73	85	109	98
M5～	15	12	9	10	12	10	16	13	8	13	11	15
M6～	2	1	2	2	-	-	1	3	2	4	3	3

The Kobe earthquake of 1995 (The Great Hanshin earthquake) whose magnitude is 7.3, as well as the Niigata earthquake of 2004 (The Mid Niigata Prefecture Earthquake of 2004) whose magnitude 6.8, caused many injuries and fatalities.

The viaducts, tunnels, and electrical facilities of the railway system suffered extensive damage during the Kobe earthquake in 1995. Fortunately, because the earthquake occurred in the early morning, there were no injuries or fatalities associated with the railway system. During the Niigata earthquake of 2004, a high speed Shinkansen train running at 203 km/h derailed. While also in this case there were no injuries or fatalities, the derailment had the capability of being disastrous. In fact, several fortunate events occurred. First, the Shinkansen remained on the track without turning over, even though it was subjected to heavy earthquake motion. Second, there was no major damage to the viaducts from the time when the earthquake vibration reached the Shinkansen to the time when the train stopped.

In part, the consequences of the Niigata derailment were minor due to triggering of the Seismic Early Warning System (SEWS). The SEWS automatically stops the trains as soon as an earthquake whose

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[1] Japanese Magnitude that set by Me theological Agent in Japan

magnitude is over a certain level is known to have occurred. The hypocenter of the Niigata earthquake was directly below a populated area not far from the Shinkansen location. In this case, the time it takes for the strong motion to reach the area of impact is short. Thanks to this warning system, the alarm was issued 2.4 seconds before the arrival of the heaviest and damaging vibrations, and the Shinkansen was able to brake consequently. The distance traveled by the Shinkansen was shortened and this contributed to preventing any serious injuries from occurring.

An important mission of organizations that provide public services to many customers is to maintain the highest level of safety. Even if the danger comes from a natural disaster and not a man-made one, one must keep dangerous situations for the customers to a minimum.

East Japan Railway Company (JR East) is the largest passenger railway company in the world. It has a 7,526.8-kilometer rail network which covers the eastern half of mainland Japan including the Tokyo metropolitan area, and about 16 million passengers use the system every day. Considering the heavy usage by customers, JR East should make persistent efforts to improve the safety level.

JR East constructed all facilities including stations, viaducts, bridges and tunnels, to conform to the earthquake design standards imposed by the Ministry of Land, Infrastructure and Transportation in Japan. Furthermore, they implemented an early seismic warning system and implemented seismic retrofitting measures for viaducts along all the Shinkansen lines. In spite of all this, it is still important that JR East use more detailed and effective methodologies to assess possible damages and losses to their railway network caused by earthquakes.

JR East developed a system to estimate the frequency of derailments and operational delays. There are, however, several factors that the current system ignores.

First, the consequences in terms of injuries or fatalities cannot be estimated in the current system. In order to make effective investments in countermeasures, the estimation of the consequences is of great importance. The consequences depend on several conditions such as the date, time, and local geology and topography. Conditions of the train at the time of the earthquake are also important (train speed, train load, type of track support, etc.) Finally, what happens after derailment greatly affects the consequences. For example, the number of casualties depends on whether the train remains standing on the track or turns over, whether it falls from significant height or collide with an incoming train, etc. All possible conditions should be taken into account in assessing the possible range of consequences.

The current system assumes that the Shinkansen trains run on viaducts. However, there are also bridges, tunnels and embankments on the Shinkansen tracks. The difference in vibration level and damage for different track conditions should be considered. In the Niigata case, it was reported that one of the significant causes of derailment was the phase difference in the seismic vibration of adjacent viaducts (Nakamura, 2005).

In order to estimate the earthquake risk for the entire JR East network (not just for each line segment in isolation from the rest of the system), it was decided to address three main issues.

1 Develop an improved Earthquake Derailment Model considering mutual effects of different soil and infrastructure conditions.
2 Develop a Consequence Model: The consequence model focuses on the estimation of casualties and fatalities including all major post-derailment scenarios such as overturning, falling, and intrusion, as well as train speed.
3 Develop a Regional Approach to risk evaluation: The regional approach estimates the system-wide rates of derailment and consequences by combining a seismicity model with the earthquake derailment and consequence models mentioned above.

This study focuses on objectives 2 and 3.

In chapter 2, we discuss the Consequence Model. The model consists of two sub-models. First we explain the development of the Derailment on Own Track Model by examining the actual derailment data. Second, we define the Collision and Train Fall Model produced by the numerical simulation results. Associating these sub-models, the consequences of most of all possible scenarios after derailment can be estimated.

In chapter 3, we describe the Regional Approach to risk evaluation. In the model, associating the derailment model and the consequence model that we mentioned above, and using real databases such as train timetable, land registers, etc, the derailment risk in the entire network can be simulated. First we explain the calculation flow and methodologies of this approach. Second, we try to compare the results between the current system of JR East and the new developed system. Third, we demonstrate the new system for the Tohoku Shinkansen line to confirm the ability of the new system.

2 Model of Derailment Consequences

In this chapter, we will discuss the development of a model to estimate the severity of consequences caused by derailments. The consequences, in terms of the number of casualties and fatalities, are not predicted by the "Shinkansen Earthquake Impact Assessment System" (Shimamura et al. 2006) currently in use by the East Japan Railway Company (JR East). Losses are influenced by pre- or post-derailment conditions. For example, if many passengers are on a derailing train, the number of casualties and fatalities is necessarily higher than if fewer passengers are on board. If the derailed train runs at a higher speed, the train might not be able to remain on the track and the losses would also increase.

First, we use a derailment data set compiled by SRI International (Klopp et al., 1996) to quantify 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. Then, we develop a Collision Model to estimate the number of casualties and fatalities in the cases of head collision with an incoming train and fall from a viaduct following derailment.

First, we used the SRI International study to compile a data set of train derailment that includes train speed, secondary accidents after derailment, track conditions, and other variables. After derailment, the train cannot run smoothly and can cause injury to passengers. If the train does not overturn and stops in a relatively safe manner, the losses are far lower than if the train overturns after derailment. In commenting on their own data of derailment events in the U.S., SRI International noted that "although the number of injuries tends to increase with speed, the number of injuries is not a simple function of the train speed." They further remarked that "derailment accidents in which many injuries occurred typically involved circumstances in which the train cars did not remain in lines and upright but instead jackknifed, overturned, or collided with other cars or track-side objects." As an anecdotal validation of this statement, one may observe that during the Niigata earthquake, even though the derailed Shinkansen was running at 203km/h when the earthquake occurred, there were no injuries or fatalities because the train remained standing on the track until it stopped. Secondary accidents after derailment, such as turnover, falling, or collision with nearby structures or with incoming trains can have large effects on the number of casualties and fatalities. Therefore, derailment cases were classified according to types of secondary accidents. Derailments that occurred in a curve were also noted, because it is more difficult that a derailed train remains upright if derailment occurs in a curve than in a straight line segment.

We used the compiled data set to investigate the dependence of the number of casualties and fatalities on train speed at the time of derailment and on other factors as indicated above. The model we use is the linear logistic type, meaning that the logit of the loss variable of interest is assumed to depend linearly on various regressions, see section 2.2.

The SRI International data does not allow one to assess the loss effects of collision with other train or fall from significant heights. To quantify their effects, we develop a separate "Collision Model" and "Falling Model" with focus on head injuries. Specifically, we investigate the connection between the Head Injury Criterion (HIC) and damage to occupants in a train that collides with other trains or fall from different heights.

In this chapter, we discuss following topics.

- Development of Consequence Model
  - Available derailment consequence data
  - Data analysis
  - Results of Logistic analysis
- Consequence Model for Collision and Falling
  - Occupant space lost
  - Secondary Impact velocity
  - Development of the collision and falling model by combination of sub-models

2.1 Available Derailment Consequence Data

SRI International (1996) considered 71 passenger train accidents in the U.S. First we reviewed their accident reports such as train speed, train operating environment, and surrounding conditions at the time of the accident. The database includes not only derailments, but also other accidents such as fire and collision. The number of casualties is divided into three categories: fatal, serious and minor. From the 71 cases, we extracted 30 derailment cases and used them for quantitative analysis. We also included two derailment accidents that occurred recently in Japan. Table 2-1 shows the data for all 32 accidents.

Table 2-1: Derailment Data Investigated by SRI international

Ref#	Date/time				Train Speed [km/h]	No. csualties and fatalities				Secondary Accidents			Curve
						Total	Fatal	Serious	Minor	Overturn	Falling	Collision	
1	1995	Oct	9	1:40	80	268	1	12	88		●		
3	1994	May	16	4:36	120	438	1	1	120				
5	1993	Sep	22	2:53	117	220	47	4	101	●	●		
7	1991	Jun	31	5:01	128	429	8	12	65				
8	1991	Dec	17	11:25	115	182	0	11	50				●
9	1990	Apr	23	13:26	124	365	0	1	85				
10	1990	Mar	7	8:21	53	182	4	6	153			●	
12	1988	Aug	5	15:15	127	368	0	6	100				
13	1988	Jan	29	12:36	140	143	0	2	23				
18	1986	Oct	9	12:21	112	233	1	2	28				
19	1986	May	18	14:09	95	1006	0	19	158				
23a	1984	May	29	18:40	60	153	0	4	19				
23b	1985	Apr	16	19:25	48	146	0	16	21				
24	1985	May	15	10:11	12	157	0	0	72			●	
25	1984	Jul	7	6:50	97	294	5	29	50		●		
28	1984	Mar	17	17:27	25	1503	0	0	19				
29	1984	Mar	5	18:45	127	293	0	13	52				
30	1983	Nov	12	10:09	115	162	4	25	47				●
31	1978	Feb	24	2:10	72	534	0	1	25				
32	1983	Apr	3	5:55	77	349	0	0	24				
34	1982	Jun	15	3:15	118	315	1	16	11				
35	1982	Jan	13	16:30	17	1323	3	5	20			●	
38	1981	May	26	12:30	122	150	0	2	13				
40	1980	Cot	30	20:37	102	108	0	1	5				
45	1980	Mar	14	16:00	60	190	0	35	80		●		●
47	1978	Feb	24	2:10	72	534	0	0	25				
48	1979	Oct	2	6:10	125	177	2	59	63				●
49	1978	Dec	12	16:06	32	103	0	0	23	●			
50	1979	Mar	28	17:50	120	109	0	15	33				
56	1977	Jan	16	4:15	70	129	0	3	73				●
JR1	2004	Oct	23	5:56	203	151	0	0	0				
JR2	2005	Dec	26	19:14	105	40	5	10	22	●		●	

The database includes three consequence categories - minor injuries, serious injuries and fatalities. The number of minor injuries tends to prevail, followed by serious injuries and finally by fatalities; see Figure 2-1.

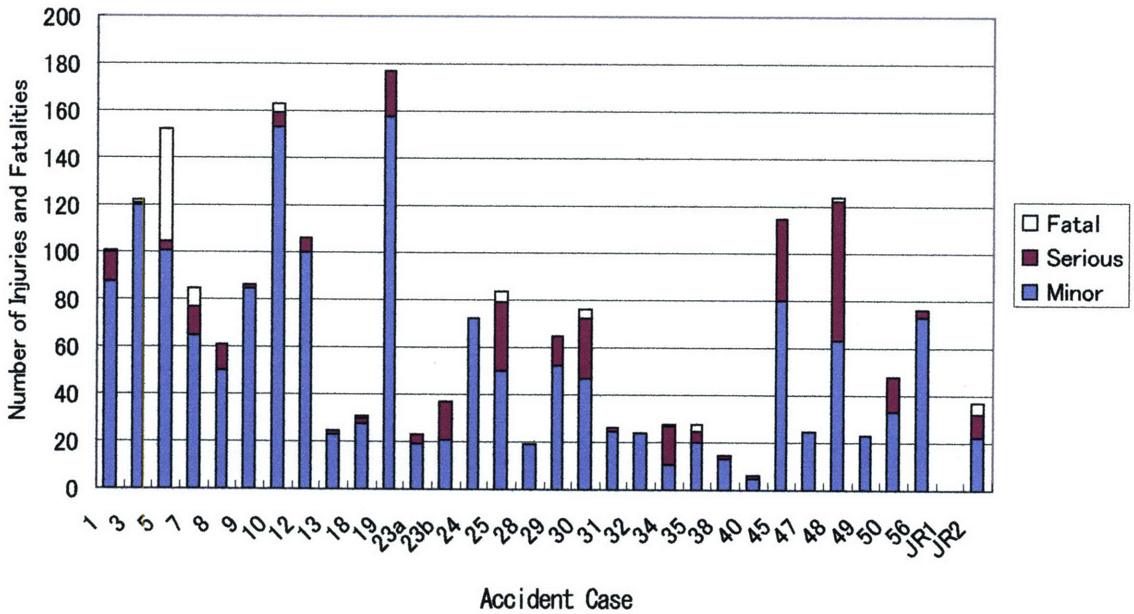


Figure 2-1: The Number of Injuries and Fatalities for Each Accidents

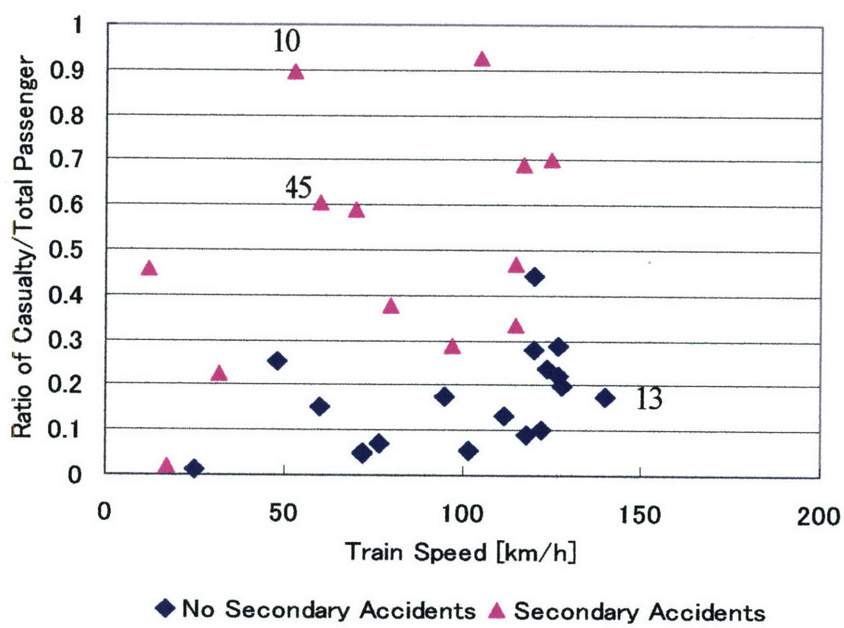


Figure 2-2: Casualty Ratios in Derailment Accidents as a Function of Train Speed

Figure 2-2 shows the casualty ratio (the number of all casualties or fatalities divided by the total number of passengers) as a function of train speed. A distinction is made between cases with no secondary accidents (diamonds) and cases in which a secondary accident occurred after derailment (triangles). Secondary accidents include turnover, falling and intrusion with sidewall. Clearly, the casualty rate is lower in the case of no secondary accident. For example, in case 10, the train ran at low speed, 53km/h, but the total casualty ratio was about 90%. This accident occurred on a subway and the train intruded into the sidewall. In case 45, although the train was also running at low speed, the train turned over after derailing because the accident occurred on a curve. The casualty ratio in that case was over 60%. By contract, in case 13 the train was running at 140km/h (the highest speed in the database), but the casualty ratio was less than 20%. In general, high speed accidents with a low casualty ratio are cases in which the train remained on the track without secondary accidents occurring.

There were two accidents that occurred on the JR East network that are also good examples to show the effect of secondary accidents on the casualty rate. One is the Niigata earthquake of 2004 which was commented earlier. The second case is a conventional train that derailed due to a downburst (a strong local wind) in 2005. In that case the train was running at 100km/h, and collided with a nearby house. Five people were killed and 32 people were injured. From these observations, one concludes that secondary accidents contribute significantly to the number of casualties and fatalities

Some basic accident statistics are given in Table 2-2. The empirical probability of severe secondary accidents without considering train speed or other conditions is 9 / 32 = 0.281.

In the SRI database, train speeds range from 12 to 140 km/h, but the Shinkansen can run well over 200 km/h and much higher speeds are planned for the future. In order to use the Shinkansen at speeds over 360 km/h in service, JR East made test runs of two prototype trains starting in 2005. At these high speeds, depending on track conditions such as curve or tilt, we expect that secondary accidents may occur at a higher rate. The empirical probability of secondary accidents plus accidents on a curve was (9 + 5) / 32= 0.438.

The data unexpectedly indicates that the number of derailments without severe accidents increases as the train speed increases. This is probably due to small sample size.

Table 2-2: Itemized Secondary Accidents in Derailment Cases

Total Number of Derailment Cases			32
	No Secondary Accidents (Moderate Case)		23
	Severe Secondary Accidents (Severe Case)		9
		Turn Over	3
		Fall	4
		One of four is also counted as a "Turn Over" case.	
		Side Intrusion	4
	Accidents on a Curve		5

2.2 Data Analysis

In order to quantify the consequence of derailment, we introduced a linear logistic model, and used least squares or weighted least squares to fit the model to the above derailment data to identify the simplest suitable model structure, we used a stepwise regression approach. Before we present results of the analysis, we discuss the overall methodology.

Linear Logistic Regression

The casualty and fatality rates are near zero for mild accidents and generally increase as the severity of the accident increases. In a previous report (Martland, 2005)0, this tendency was expressed by assuming an exponential function, $1\text{-}e^{a}$. In the function, a severity index and the function approaches to 1 as the severity increases. Here we prefer to work with the logit of the casualty and fatality ratios R_i that will explain in the following section, defined as:

$$\begin{aligned} Logit(R_i) &= \log(\frac{R_i}{1-R_i}) \\ &= \log(R_i) - \log(1-R_i) \end{aligned} \qquad \textbf{2-1}$$

The exponential function ranges from zero to infinity, whereas the logit ranges from $-\infty$ to $+\infty$. Suppose that $Logit(R_i)$ varies linearly with one or more explanatory variables X_j as

$$Logit(R_i) = a + \sum_k b_k g_k(\underline{X}) \qquad \textbf{2-2}$$

where $\underline{X}$ is the vector of the X_j and the $g_k(\underline{X})$ are given functions of X and a and the b_k are parameters. If one considers only train speed TS as an explanatory variable and the logit of R_i depends linearly on g(TS) = ln(TS), then equation 2-2 is defined as

$$Logit(R_i) = a + b \ln TS \qquad \textbf{2-3}$$

with parameters a and b. Then, solving equation 2-2 for R_i gives:

$$R_i = \frac{e^{a+\sum b_k g_k(\underline{X}_k)}}{1+e^{a+\sum b_k g_k(\underline{X}_k)}} \qquad \textbf{2-4}$$

Estimation of the parameters a and b_k, in equation 2-2 is a problem of logistic regression. Once these parameters are estimated, the casualty and fatality rates R_i can be determined from 2-3.

As we discussed in the section 2.1, the number of casualties tends to increase with train speed and is affected by other factors such as turnover, fall, track curvature, etc.

Fraction of Casualties and Fatalities

In order to analyze minor casualties, serious casualties, and fatalities, three rates R_i are introduced as follows:

$$R_1 = \frac{M+S+F}{N_{Total}}$$
$$R_2 = \frac{S+F}{M+S+F} \qquad \textbf{2-5}$$
$$R_3 = \frac{F}{S+F}$$

where M and S are the number minor and serious injuries, F is the number of fatalities, and N_{Total} is the total number of passengers on the train.

Using the rates in equation 2-5, the fractions of people who are lightly injured, severely injured or killed in a derailment are recovered as:

$$R_F = \frac{F}{N_{Total}} = R_1 \times R_2 \times R_3$$
$$R_S = \frac{S}{N_{Total}} = R_1 \times R_2 \times (1 - R_3) \qquad \textbf{2-6}$$
$$R_M = \frac{M}{N_{Total}} = R_1 \times (1 - R_2)$$

Clearly, the sum of $R_F + R_S + R_M$ should not exceed 1. If R_F, R_S and R_M were modeled directly without relating them to R_1, R_2 and R_3, the sum of R_F, R_S and R_M could possibly exceed 1, because there are no restrictions on the total number of passengers. The advantage of expressing the consequences through the ratios Ri in equation 2-5 is that each of these ratios can vary between 0 and 1. The ratios R_F, R_S *and* R_M will then satisfy $R_F + R_S + R_M \leq 1$.

Choice of X_j Variables

Equation 2-3 illustrates the logistic model when only one factor (train speed) influences the ratio R_i. In reality, other factors such as turnover, train fall, side intrusion, or the existence of curve are also likely to be influential. Moreover, we want to simultaneously model all three rates R_1, R_2, and R_3. The following factors are used in the linear regression model as regressions X_j :

- Ratio index i ($i = 1,2,3$)
- Train speed, *TS*
- Occurrence of secondary accidents of different types (Overturn / Falling / Collision)
- Curve or straight tracks

Table 2-3 shows how these variables are expressed.

Table 2-3: Definition of Possible X_i Variables

Variables	Value	Definition
X_{TS}	$= \ln TS$	Natural logarithm of train speed
$X_{overturn}$	$= \begin{cases} 0 \\ 1 \end{cases}$	If overturn occurs $X_{overturn} = 1$, otherwise $X_{overturn} = 0$.
$X_{falling}$	$= \begin{cases} 0 \\ 1 \end{cases}$	If falling occurs $X_{falling} = 1$, otherwise $X_{falling} = 0$.
$X_{collision}$	$= \begin{cases} 0 \\ 1 \end{cases}$	If collision occurs $X_{collision} = 1$, otherwise $X_{collision} = 0$.
X_{curve}	$= \begin{cases} 0 \\ 1 \end{cases}$	If curvature exists $X_{curve} = 1$, otherwise $X_{curve} = 0$.
X_1, X_2	$= \begin{cases} 0 \\ 1 \end{cases}$	Binary variables to indicate the type of ratio R_i considered; $(X_1, X_2) = (0, 0)$ for R_1, $(1, 0)$ for R_2, $(0, 1)$ for R_3.

Later in the analysis, we find it necessary to replace $X_{overturn}$, $X_{falling}$, $X_{collision}$ and X_{curve} with a simple indicator variable for severe accidents of any kind or for derailment on curved tracks. This variable, X_{severe}, is 1 if overturn, fall or collision occurs or if derailment occurs on a curve. Otherwise $X_{severe} = 0$.

Choice of Possible $g_k(\underline{X})$ Functions

A function $g_k(\underline{X})$ that depends only on one regression variable X_k is said to model the "main effect" of X_k. Functions of two or more variables quantify so-called "interactions." A simple way to specify the functions g_k is as follows:

In derailment cases, the dependent factor might not only be one "main effect" but also have "interaction" each other. For instance, if there are no secondary accidents, the minor injuries might be most prevalent, but if any secondary accidents happen, the severity level will change, and more serious injuries or fatalities will occur more often. The severity of accident relates to the severity of consequence. In order to simulate these characteristics, we should choice of possible X_i combinations as $g_i(\underline{X_i})$ functions.

$$g_k(\underline{X}) = \begin{cases} X_i & \longrightarrow \text{Main effect of } X_i \\ X_i \times X_j & \\ X_i \times X_j \times X_k & \Big\} \text{ Interaction of different order} \\ X_i \times X_j \times X_k \times \cdot\cdot\cdot & \end{cases}$$

The choice of which main effects and interactions to indicate is the objective of stepwise regression.

Method of Fitting

There are several methods to fit the linear logistic model in equation 2-1. A popular one is maximum likelihood. The maximum likelihood method estimates the most likely parameter values by calculating the probability of the observations. While conceptually very appealing, the maximum likelihood has the drawback of requiring specification of a probabilistic model for the observed consequences. Formulation of such a model is quite complicated, especially when there are many possibly interacting regressions and the response is vector-valued. In our research, for example, the ratios, R_1, R_2, and R_3 for each derailment are interacting parameters. A simpler fitting method is weighted or un-weighted least squares. In these methods, one looks for the parameter values that minimize the weighted or un-weighted sum of squares.

$$\sum_{l=1}^{32}\sum_{i=1}^{3} w_{li}[Logit(R_{li})_{model} - Logit(R_{li})_{data}]^2 \qquad \textbf{2-7}$$

where l is the derailment case number, i is the type of consequence, and the w_{li} are non-negative weights. $w_{li} \equiv 1$, in the case of equal weights. When $y_i^{'} = Logit(R_i)$, $y_{i\_empirical}^{'}$ are real data values and $\hat{y}_{i\_model}^{'}$ is the estimated $y_{i\_empirical}^{'}$ by the model. If R_{li} is 0 or 1, its logit diverges and the weighted sum of squares in equation 2-7diverges. In practice, this happens mainly when one of the R_{li} is zero. Here one can deal with zero is discussed next.

Zero Casualties

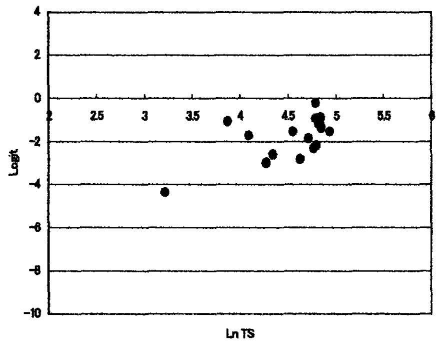
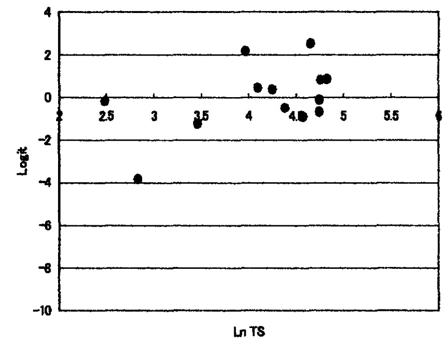
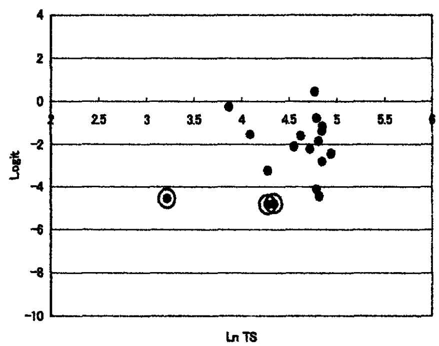
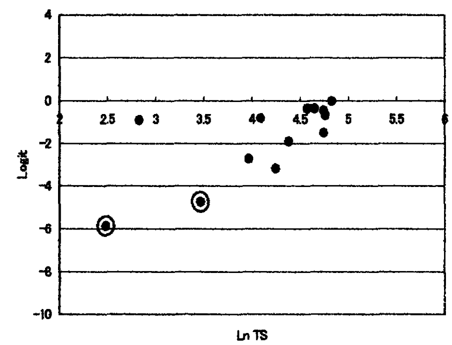
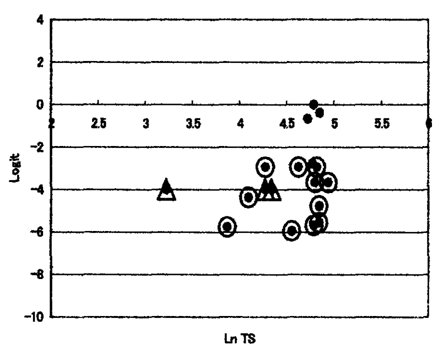
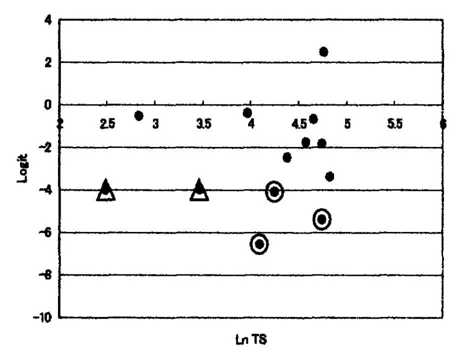
In the SRI database, some cases have zero serious injuries (S) and fatalities (F). If S+F or F is zero, some of the empirical logits $Logit(R_{li})$ diverge. To deal with this situation, one may either use a procedure that can handle the zero, like maximum likelihood, or substitute the zeros with small positive numbers. Here we use least squares and replace the zeros with small positive numbers.

To find appropriate substitute numbers for the zeros, the non-zero values in the data should be examined, since the artificial ratios R_{li} using the substitute values should not exceed the ratios that utilize the actual positive data values. On the other hand, the substitute numbers should not be too small or else they become too influential on the fitted model.

After examining the non-zero values, we decided to replace $S+F=0$ with $S+F=0.2$ for $S+F=0$ and with $F=0.05$ for F=0. In terms of $\frac{F}{S+F}$, we consider two values. One is $\frac{F}{S+F}=0.018$, and the other is $\frac{F}{S+F}=0.001$. The former substitute value, 0.018, is the average of the logit values when it was applied that $S+F=0.2$ instead of $S+F=0$ and $F=0.05$ instead of F=0. (Figure 2-3) The latter substitute value, 0.001, is the logit value that was set as the lower value than the *logit* values that were applied that $S+F=0.2$ instead of $S+F=0$ and $F=0.05$ instead of F=0. (Figure 2-4)

From these figures, one can see the artificial values are below and not fall apart significantly from the real values. The artificial values that are applied with 0.018 if F/(S+F)=0 (Figure 2-3), are higher than that are applied with 0.001 if F/(S+F)=0.

In the SRI database, there is also a case with $\frac{F}{S+F}=1$, which produces an infinite logit. Rather than using a substitute value for this ratio, we have decided to omit this accident from the analysis.

	Moderate Cases	Severe Cases
$R_1 = \frac{M+S+F}{N_{Total}}$		
$R_2 = \frac{S+F}{M+S+F}$		
$R_3 = \frac{F}{S+F}$		

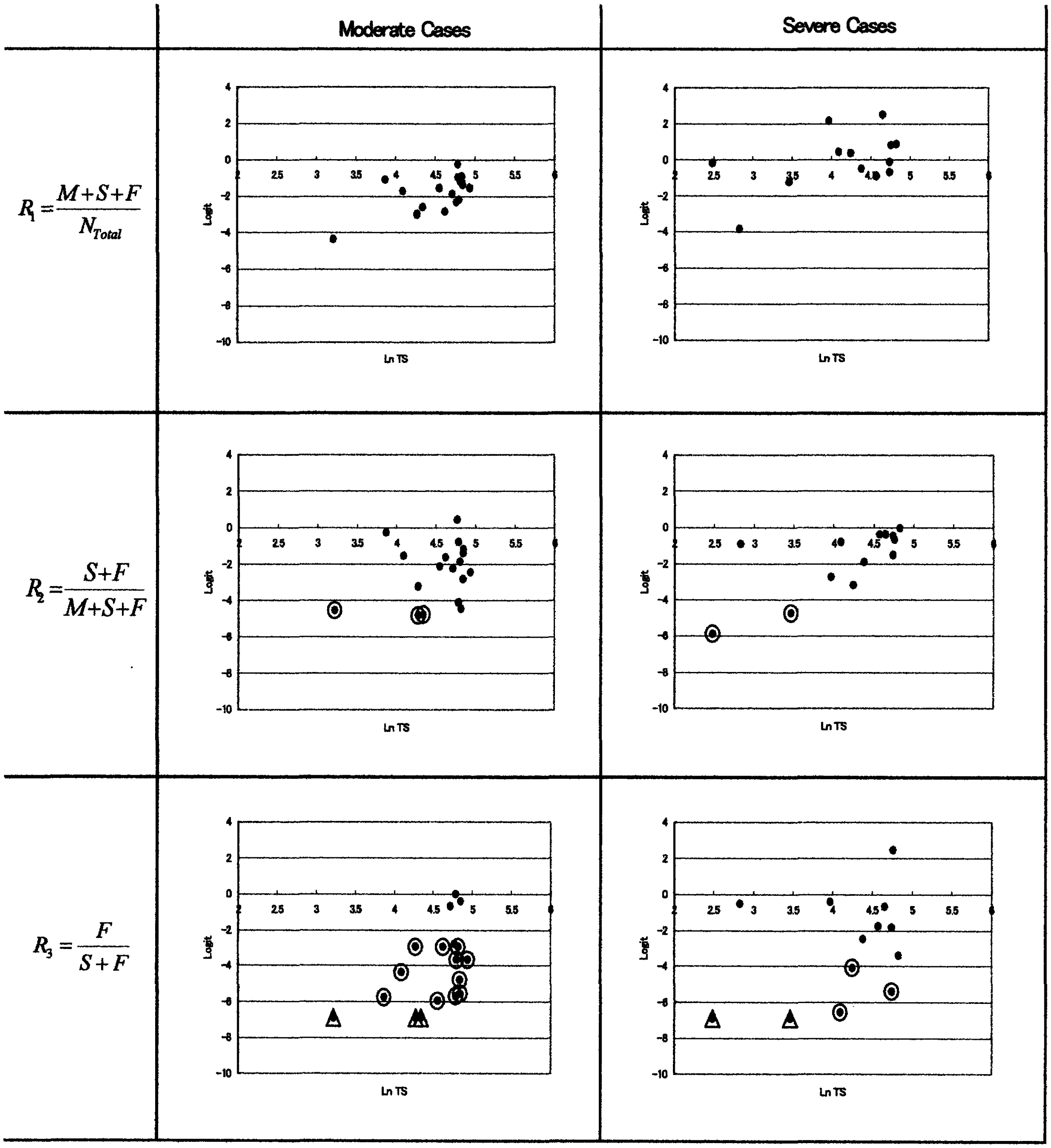
● represents real and artificial values

◉ represents the artificial values, if S+F=0, S+F=0.2, and if F=0, F=0.05.

△ represents the artificial values, if F/(S+F)=0, F/(S+F)=0.018.

Figure 2-3: Empilical Logits of R1, R2 and R3 as a Function of Train Speed

(If S+F=0, S+F=0.2, if F=0, F=0.05, and if F/(S+F)=0, F/(S+F)=0.018)



- ● represents real and artificial values
- ◉ represents the artificial values, if S+F=0, S+F=0.2, and if F=0, F=0.05.
- ▲ represents the artificial values, if F/(S+F)=0, F/(S+F)=0.001.

Figure 2-4: Logits of R1, R2 and R3 as a Function of Train Speed
(If S+F=0, S+F=0.2, if F=0, F=0.05, and if F/(S+F)=0, F/(S+F)=0.001)

Case of Niigata Earthquake in JR East

As already noted, the derailment of the Shinkansen during the 2004 Niigata earthquake occurred when the train was running at high speed (203km/h), but produced no injury and fatality. Rather than assigning substitute values to the R_i rates, we have decided to omit also this event. After fitting the model to the remaining data, one finds that the outcome of the Niigata derailment is not out of line with the other cases, if one consider that no secondary accident occurred in the Niigata event

2.3 Results of Logistic Analysis

Strategy for Selection of Model

To identify a suitable simple model, one may start by fitting a model with many parameters and progressively eliminate the parameter terns that are statistically less significant. This idea may be pursued formally thorough so-called stepwise regression and statistical hypothesis testing. Alternatively, one may use the results of statistical analysis to judgmentally identify the best model structure. The latter approach allows one to include physical consideration in the process of model selection. The judgmental approach was implemented by first fitting a highly parameterized model in which the coefficients a and b_k in equation 2-2 are allowed to vary depending on the type of consequence i, whether derailment occurs on curve tracks, and whether derailment is followed by a secondary accident (overturning, falling, intrusion). The model has the form;

$$\begin{aligned} Logit(R_i) = a + b_0 X_{TS} & \\ + \Delta a_{overturn} X_{overturn} + \Delta b_{overturn} X_{TS} X_{overturn} & \\ + \Delta a_{fallling} X_{falling} + \Delta b_{fallling} X_{TS} X_{falling} & \\ + \Delta a_{\text{int}\,rusion} X_{\text{int}\,rusion} + \Delta b_{\text{int}\,rusion} X_{TS} X_{\text{int}\,rusion} & \\ + \Delta a_{curvature} X_{curvature} + \Delta b_{curvature} X_{TS} X_{curvature} & \\ + \Delta a_1 X_1 + \Delta b_1 X_{TS} X_1 & \\ + \Delta a_2 X_2 + \Delta b_2 X_{TS} X_2 & \end{aligned} \qquad \textbf{2-8}$$

where $X_{TS} = ln\ TS$, and $X_{overturn}, X_{falling}, X_{intrusion}$ and $X_{curvature}$ are binary variables to indicate overturning, falling, or collision, and whether derailment occurs on curved tracks.

Table 2-4: Regression Results (Coefficients and Standard Error)

Regression Statistics	
Multiple Correlation R	0.726
R-square R2	0.527
Standard Error	1.640
Observation	93

	Coefficients	Standard Error
a	-7.105	2.910
$\Delta a_{overturn}$	-0.130	1.346
$\Delta a_{falling}$	4.215	3.232
$\Delta a_{collision}$	0.273	0.866
$\Delta a_{curvature}$	0.028	1.930
Δa_1	0.580	0.682
Δa_2	0.756	0.682
Δb_0	1.199	0.648
$\Delta b_{overturn}$	0.661	5.492
$\Delta b_{falling}$	-17.142	14.359
$\Delta b_{collision}$	2.054	3.276
$\Delta b_{curvature}$	0.867	8.911
Δb_1	-3.597	3.006
Δb_2	-5.777	3.006

Because of the limited data, it is difficult to reliably estimate all the parameters in equation 2-8. The parameter values as results of regression for equation 2-8 are shown in Table 2-4. "Multiple Correlation", which can indicate the strength and direction of a linear relationship between the objective data and the estimated parameters, is not small. However, estimated parameters in some cases are not physically reasonable. For example, some slopes, $\Delta b_{falling}$, Δb_1, and Δb_2 have negative. This means the severity of them are decreasing as the train speed increase. Half of parameters has the standard errors that are larger than the coefficients. This means the estimated parameters are not stable values.

To simplify the model, we have constrained the Δa and Δb paramaters assembled with different secondary accidents and with curved tracks to be the same. Using the X_{severe} indicator valiable, the model becomes as follows;

$$\begin{aligned} Logit(R_i) = a + b_0 X_{TS} \\ + \Delta a_{severe} X_{severe} + \Delta b_{severe} X_{TS} X_{severe} \\ + \Delta a_1 X_1 + \Delta b_1 X_1 X_{TS} \\ + \Delta a_2 X_2 + \Delta b_2 X_2 X_{TS} \end{aligned} \qquad \textbf{2-9}$$

where X_{severe} is a binary variable to represent relatively severe accidents such as turnover, falling, side intrusion, or curved tracks. Results are shown in Figures 2-5, 2-6, and 2-7.

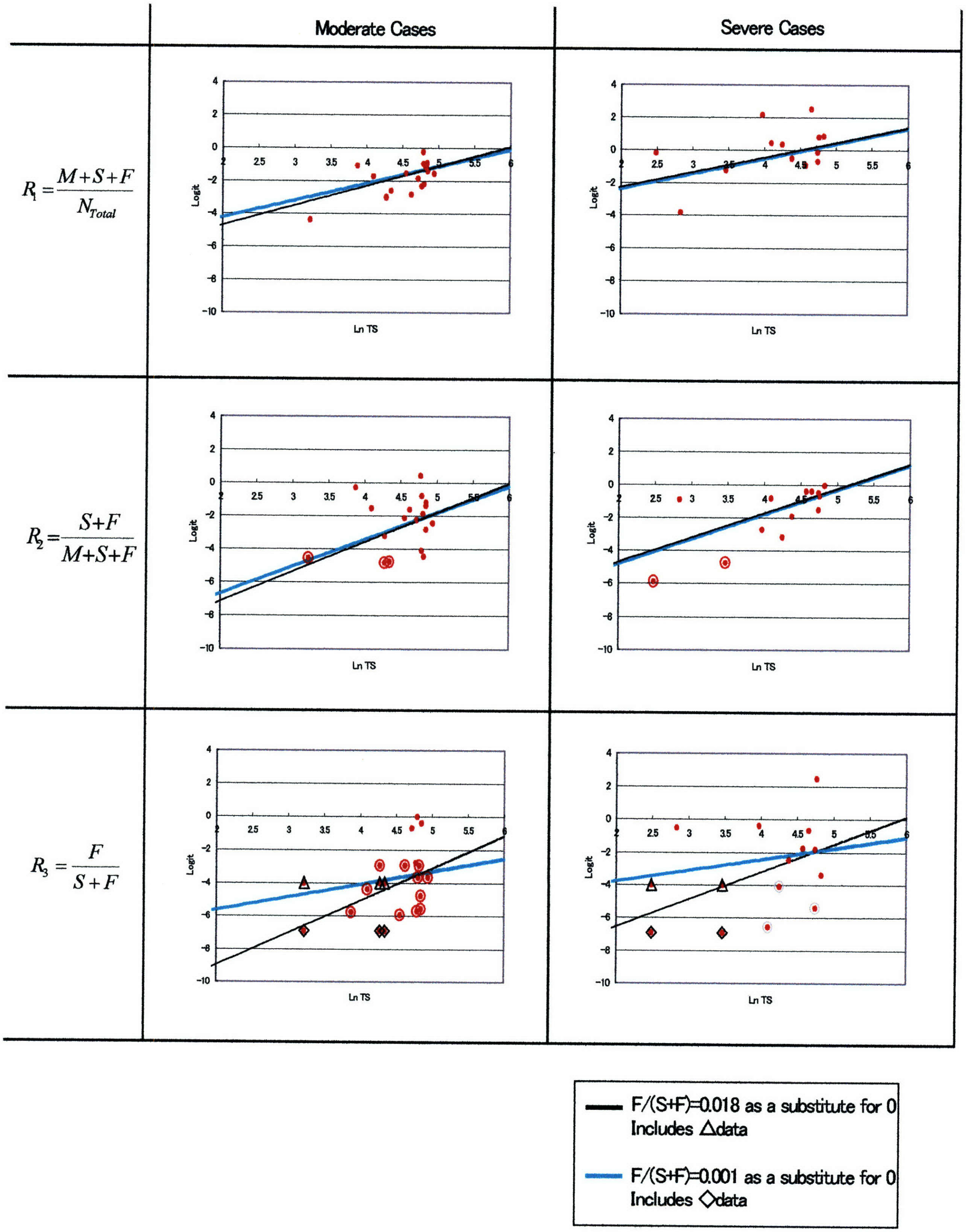


Figure 2-5: Logits of R1, R2 and R3 as a Function of Natural Logarithm of Train Speed

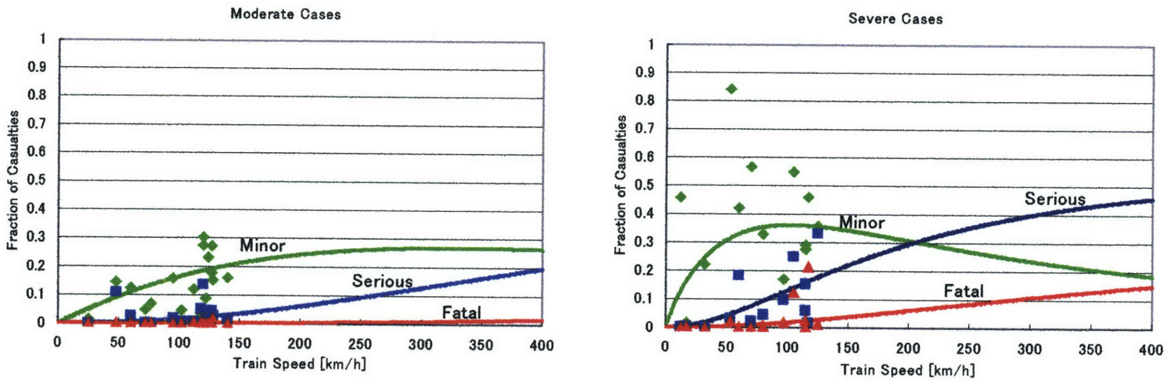


Figure 2-6: The Result of Model in Eq. 2-9 fitted by Least Square after putting $F/(S+F)=0.018$ when $S=F=0$

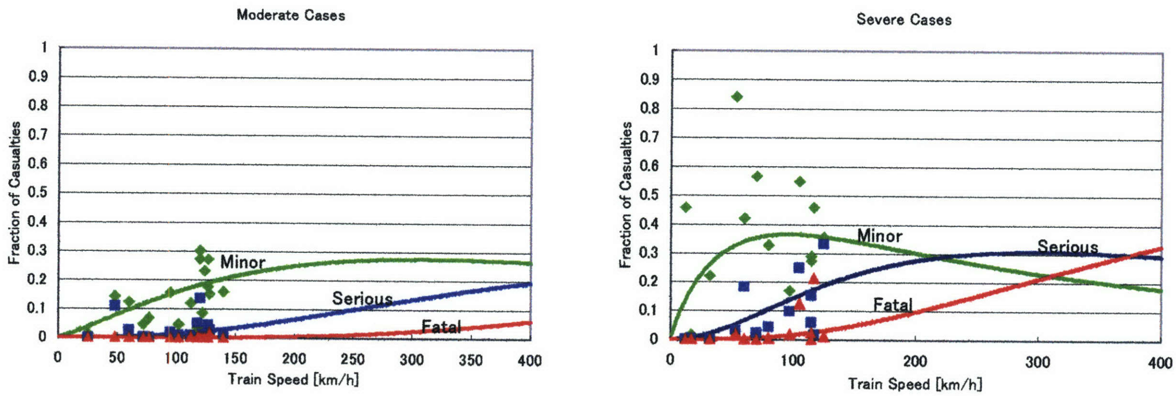


Figure 2-7: The Result of Model in Eq. 2-9 fitted by Least Square after putting $F/(S+F)=0.001$ when $S=F=0$

Consider first the case of mild derailment ($X_{severe}=0$). In this case, results are insensitive to setting F / (S+F) = 0.018 or F/(S+F) = 0.001 that are substitute vales when $S=F=0$. At all speeds between speeds of 0km/h to 400km/h, the rate of minor injuries exceeds the rates of severe injuries and fatalities. The latter rates increase with train speed, and the rate of minor injuries gradually decreases beyond 300km/h. Note that, as the train speed $\rightarrow \infty$, the fatality rate approaches 1 and the injury rates approach 0, but the speeds considered in Figures 2-6 and 2-7 are far from this limit.

In the case of severe accident ($X_{severe}=1$), the minor injury rate increase rapidly until 50km/h and gently decreases after 100km/h. When F / (S+F) is set to 0.018, the rate of severe injuries dominates for speeds greater than 200km/h. If F/(S+F) is set as 0.001, the fatality rate increases more rapidly and becomes dominant for speeds higher than 380km/h.

In equation 2-9, X_{severe} was only considered as a "main factor" and a 1st order "interaction" for X_{ts}. However, the level of casualties could be affected by the existence of secondary accidents. In order to examine the effect of secondary accidents to the severity levels, we introduced X_{severe} as other 1st order "interaction" for X_1 and X_2 and 2nd order "interaction" for $X_{ts} X_1$ and $X_{ts} X_2$.

$$\begin{aligned} Logit(R_i) &= a + b_0 X_{TS} + \Delta a_{severe} X_{severe} + \Delta b_{severe} X_{TS} X_{severe} \\ &+ \Delta a_1 X_1 + \Delta b_1 X_1 X_{TS} + \Delta a_1 X_1 X_{severe} + \Delta b_1 X_1 X_{TS} X_{severe} \\ &+ \Delta a_2 X_2 + \Delta b_2 X_2 X_{TS} + \Delta a_2 X_2 X_{severe} + \Delta b_2 X_2 X_{TS} X_{severe} \end{aligned} \qquad \textbf{2-10}$$

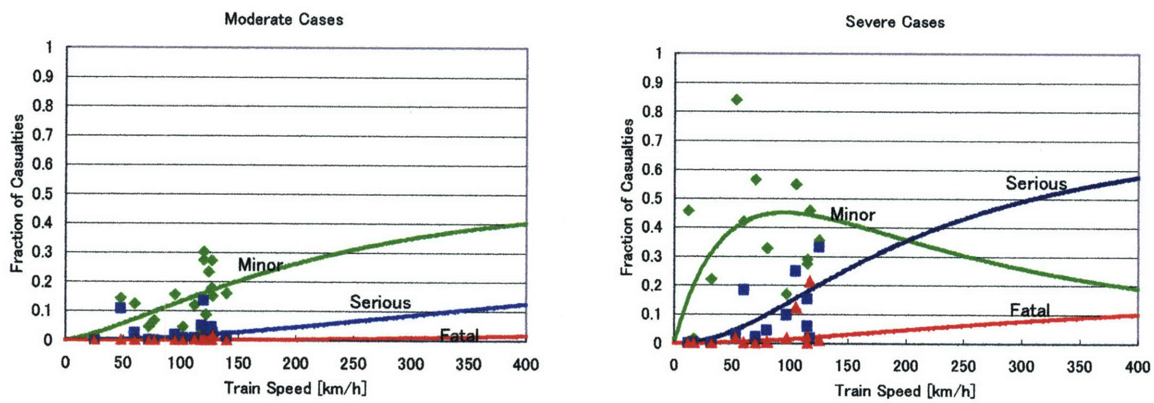


Figure 2-8: The Result of Model in Eq. 2-10fitted by Least Square after putting $F/(S+F)$=0.001 when $S=F=0$

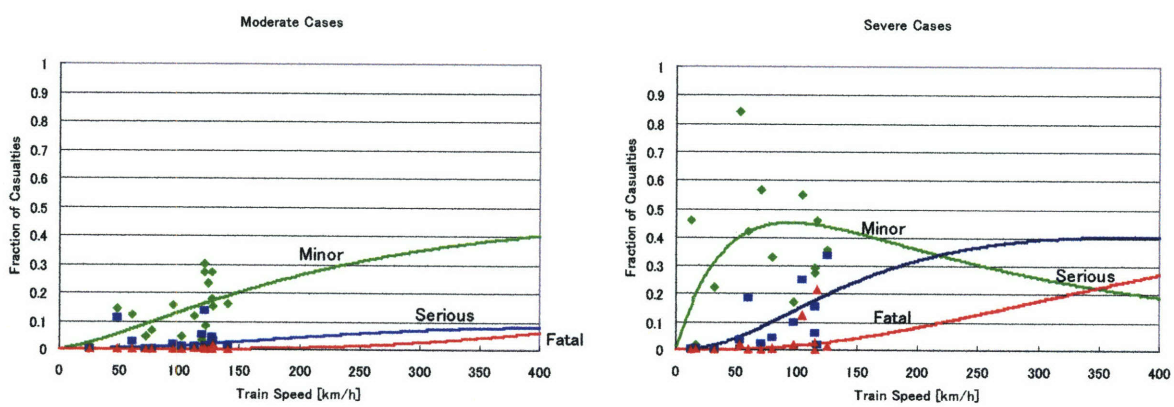


Figure 2-9: The Result of Model in Eq. 2-10 fitted by Least Square after putting $F/(S+F)$=0.001 when $S=F=0$

Although all ratios increase more significantly as speed increases than that in Figures 2-8 and 2-9, As one can see, the trends are similar to there for the simpler model, in equation 2-9. Quantitative differences are also modest.

In order to reduce the influence of the zero values, we repeated the analysis of the model in equation 2-9 using weighted least square, discussed in §2.2. The results are shown in Figures 2-10 through 2-13. The weights were set to 1 for all non-zero data points, and to either 0.1 or 0.5 for the originally zero values.

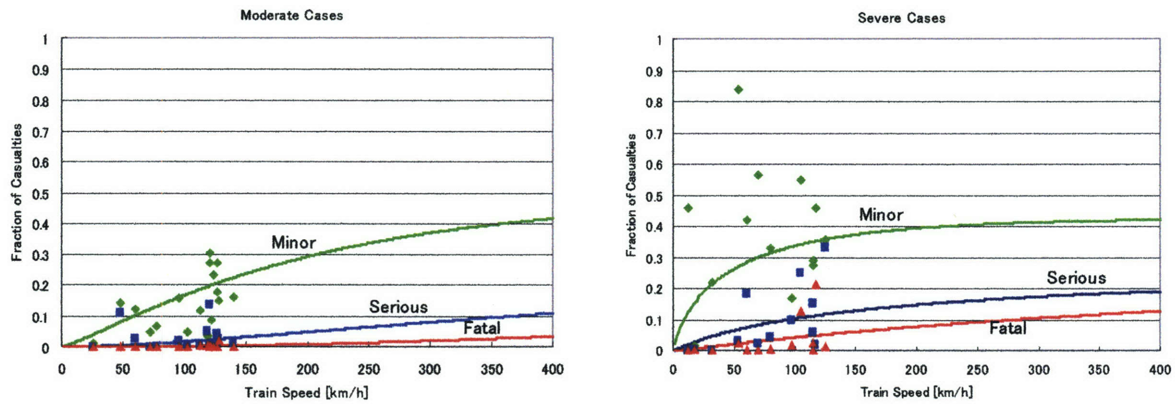


Figure 2-10: Weighted Least Squares Fitting of the Model in Equation 2-9
w_i=0.1 for the originally zero values, F/(S+F)=0.018 when $S=F=0$

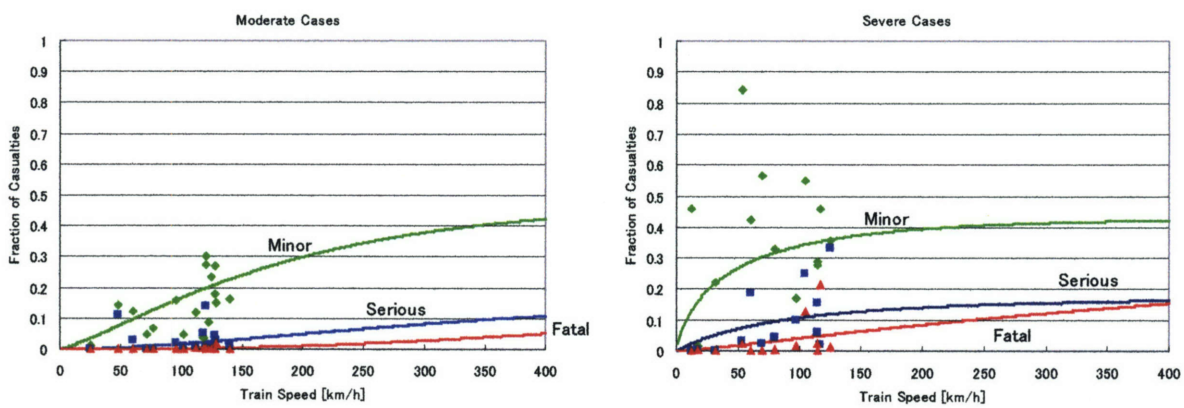


Figure 2-11: Weighted Least Squares Fitting of the Model in Equation 2-9
w_i=0.1 for the originally zero values, F/(S+F)=0.001 when $S=F=0$

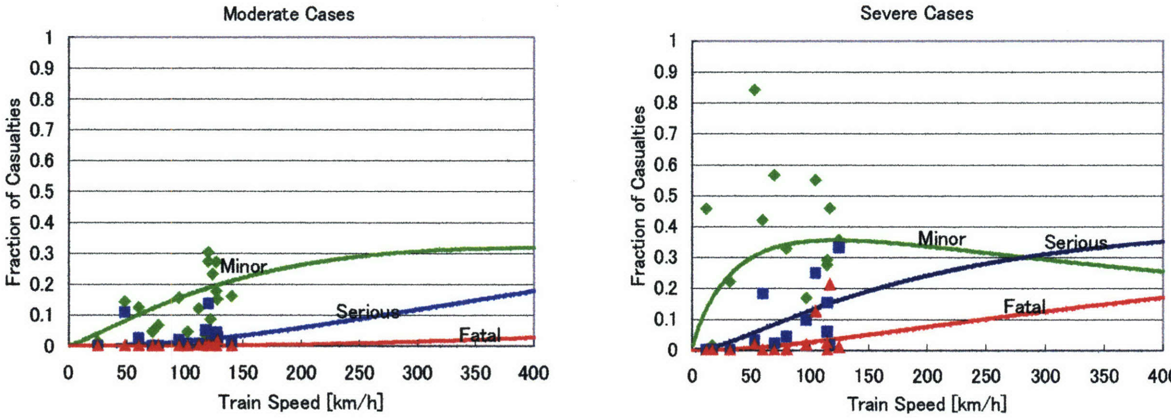


Figure 2-12: Weighted Least Squares Fitting of the Model in Equation 2-9

w_i=0.5 for the originally zero values, F/(S+F)=0.018 when $S = F$ =0

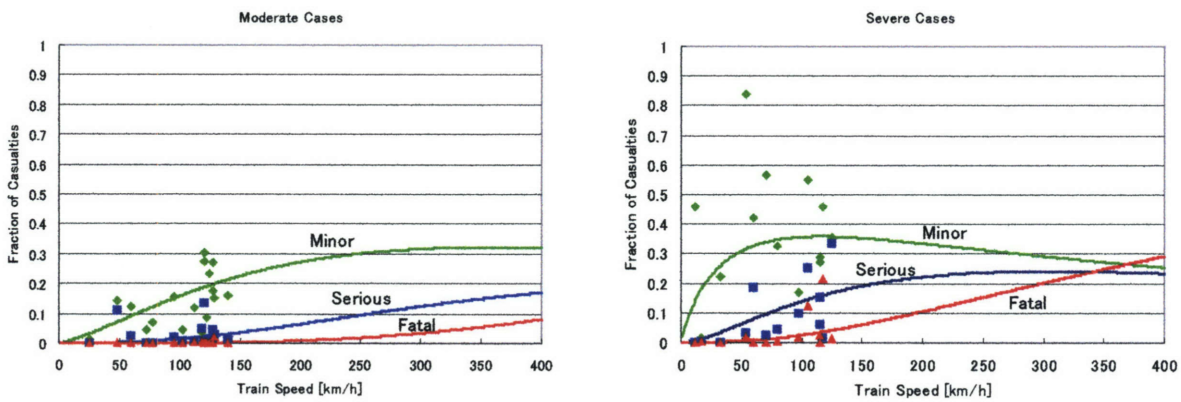


Figure 2-13 Weighted Least Squares Fitting of the Model in Equation 2-9

w_i=0.5 for the originally zero values, F/(S+F)=0.018 when $S = F$ =0

In the case in which the weight w_i is set to 0.1 for originally zero values (Figures 2-10 and 2-11), the minor injury rate dominates for both moderate and severe derailments. This is different from Figures 2-12 and 2-13. Figures 2-12 and 2-13 show trends similar to these of Figures 2-6 and 2-7, respectively.

The least squares coefficients of the model in equation 2-9 are listed in Table 2-5. These estimates are not completely satisfactory and indicate that same additional simplification of the model could be made. Notice in particular Δb_1 and Δb_2 are negative and have relatively high standard errors. Also Δa_{severe} and Δa_1 are smaller than their standard errors. Δa_2 is larger than its standard error, but the difference is small. The way zero values were treated probably affected the results. Most of the originally zero data are included in data of R_3 (= F/(S+F)). we re-fitted the model after setting Δb_2, Δa_{severe}, Δa_1 and Δa_2 equal to zero and obtained the results as Table 2-6.

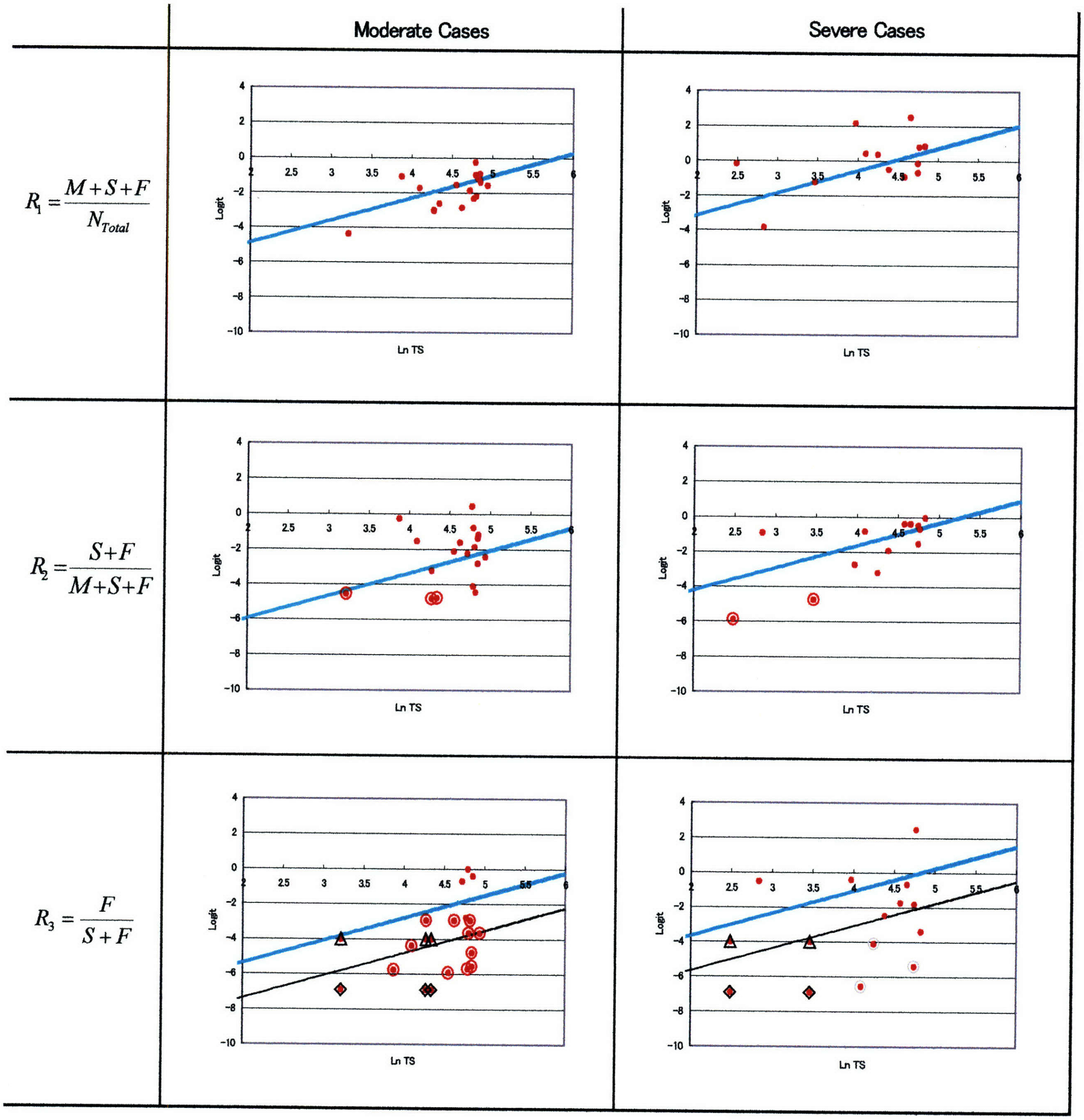
Against the results in Table 2-6, we set $\Delta \alpha_2$= -0.5 and $\Delta \alpha_2$= -2.5 judgmentally. $\Delta \alpha_2$= -0.5 is set so that the line passes through the average of data relating R_2 = F / (F+S) without originally zero data. $\Delta \alpha_2$= -2.5 was set so that the line passes through the center of data relating R_2 = F / (F+S) including the zero data. The fitting results are shown in Figure 2-14. We call this the "Modified 2-9" model.

Table 2-5: Regression Results (Coefficients and Standard Error) Using Eq. 2-9

	Coefficients	Standard Error		Coefficients	Standard Error
a	-7.089	3.066	Δb_0	1.196	0.681
Δa_{severe}	-0.289	0.658	Δb_{severe}	3.018	2.920
Δa_1	0.581	0.716	Δb_1	-3.597	3.155
Δa_2	0.756	0.716	Δb_2	-5.777	3.155

Table 2-6: Recalculated Results (after setting Δa_{over}, = Δa_1 = Δa_2= Δb_2,=0)

	Coefficients	Standard Error		Coefficients	Standard Error
a	-7.450	1.344	Δb_0	1.287	0.291
			Δb_{severe}	1.732	0.360
			Δb_1	-1.065	0.337



- ● represents real and artificial values
- ◉ represents the artificial values, if S+F=0, S+F=0.2, and if F=0, F=0.05.
- △ represents the artificial values, if F/(S+F)=0, F/(S+F)=0.001.
- ▬ (blue) regression line setting Δb_2= -0.5
- ▬ (black) regression line setting Δb_2= -2.5

Figure 2-14: Logit of R1, R2 and R3 vs. Train Speed and fits using the modifyed 2-9 model with Δa_2 set to either –0.5 and –2.5

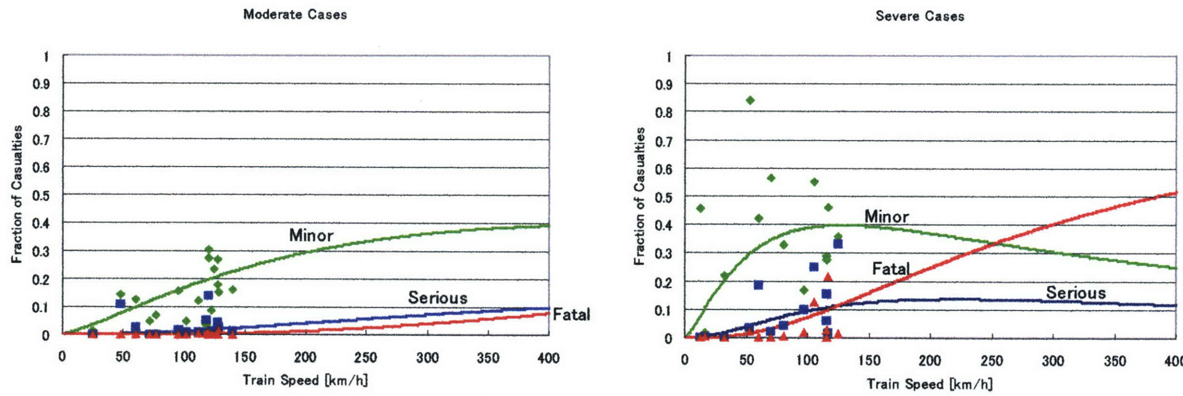


Figure 2-15: The Result of Modified Eq. 2-9 model fitted by Least Square with Δa_2=-0.5

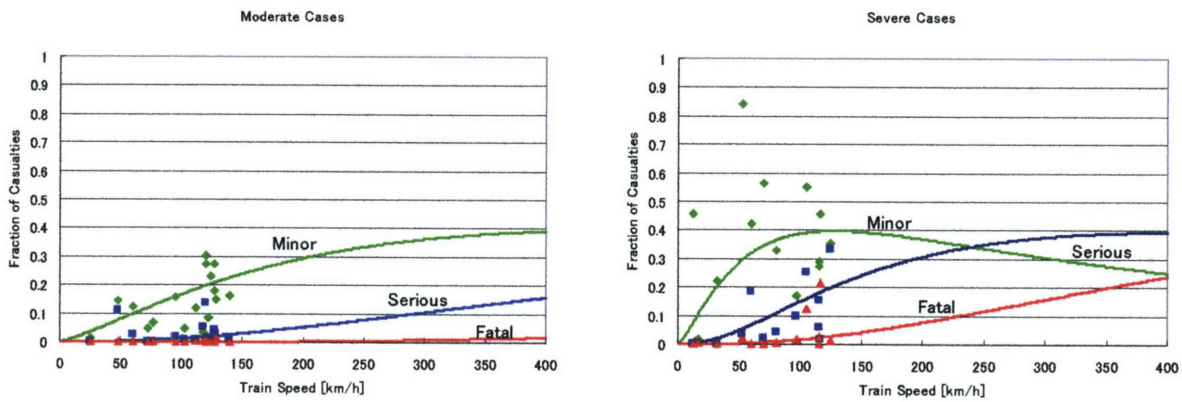


Figure 2-16: The Result of Modified Eq. 2-9 model fitted by Least Square with Δa_2=-2.5

In the case of derailment without secondary accidents (moderate case), the casualty and fatality rates increase with train speed and do not cross. This is similar to Figures 2-6 and 2-7, but minor injuries are higher, and serious injuries and fatalities are lower than in Figures 2-6 and 2-7. In fact, results are close to these in Figures 2-8 and 2-9.

In the case of secondary accidents (severe case), minor injury and serious injury rates increase more drastically than in previous figures. In the case in which Δa_2=-0.5, the fatality rate dominates in the high speed region.

Discussion of Results and Recommended Model

– Selection of model and variables

To quantify the consequences of derailment, we introduced a linear logistic model and used least squares or weighted least squares to fit the derailment consequence data that compiled by SRI International.

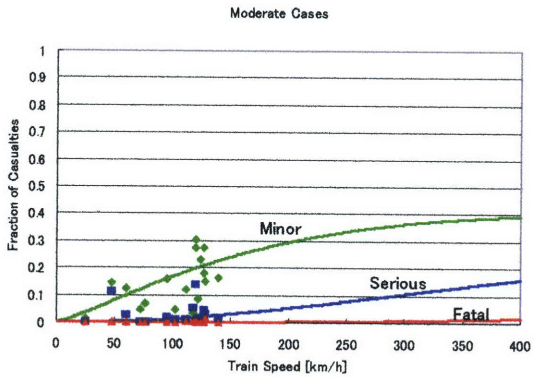
In the SRI database, there are some cases that have zero casualty or fatality. Because the empirical logits $Logit(R_{ij})$ diverge if there are zero data, we replace the zeros with small positive numbers.

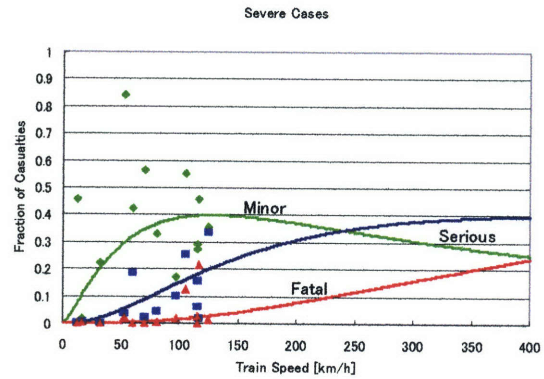
To select a suitable model structure, we used stepwise regression and statistical hypothesis testing. Because of the limitation of data on different secondary accident categories, we found X_{severe}, which can indicate the existence of overturn, fall and intrusion, and track curvature, can be used to reliably estimate the model instead of precise parameters.

– Results and Recommended Model

Using the simplified indicator variable X_{severe}, we found some common tendencies. In the case of derailment without secondary accidents, the casualty and fatality rates increase with increasing train speed and do not cross. In Severe cases, minor injury rates skyrocket at low speed, and then decrease gently. In the higher speed region, the serious injury and fatality rate becomes more prevalent.

We selected Figure 2-16 "The Judgmental Extrapolation with Δa_2=-2.5" as a recommendable consequence model. The statistical results of the model are shown in Table 2-7. In the model, the fatality rate is increasing enough and the total casualty ratio is high enough at a high speed. Since it had the higher total casualty and high fatality ratio, more severe results that might be helpful information to be prepared for the worst cases can be obtained.





Re-indicated Figure 2-16: The Result of Modified Eq. 2-9 model fitted by Least Square with Δa_2=-2.5

Table 2-7: Recalculated Results (The Judgmental Extrapolation with $\Delta \alpha_2$=-2.5")

	Coefficients	Standard Error
a	-7.450	1.344
Δb_0	1.287	0.291
Δb_{severe}	1.732	0.360
Δb_1	-1.065	0.337
Δb_2	-2.5	—

From the obtained model, one can estimate the casualty and fatality ratios, if train speed and the fact whether a secondary accident occur or not can be obtained. For example, if a derailment occurs without a secondary accident when a train runs at 100 km/h, minor injuries would be about 30% and serious injuries would be about 5% for the total passengers, and fatalities would be a few. The example ratios for different speed and the fact of a secondary accident are shown in Table 2-8.

Table 2-8: Example Results of Recommended Model

	Without Secondary Accident			With Secondary Accident		
Speed [Km/h]	100	200	300	100	200	300
Minor	0.167	0.294	0.361	0.388	0.368	0.304
Serious	0.012	0.052	0.104	0.150	0.306	0.375
Fatal	0.000	0.002	0.008	0.015	0.076	0.156

The distribution of residuals of the recommended Consequence Model is shown in Figure 2-17. Although in the first phase of this project, uncertainty of consequences is not considered in the regional approach model, it should be considered when the more precise estimation would be done in the second phase.

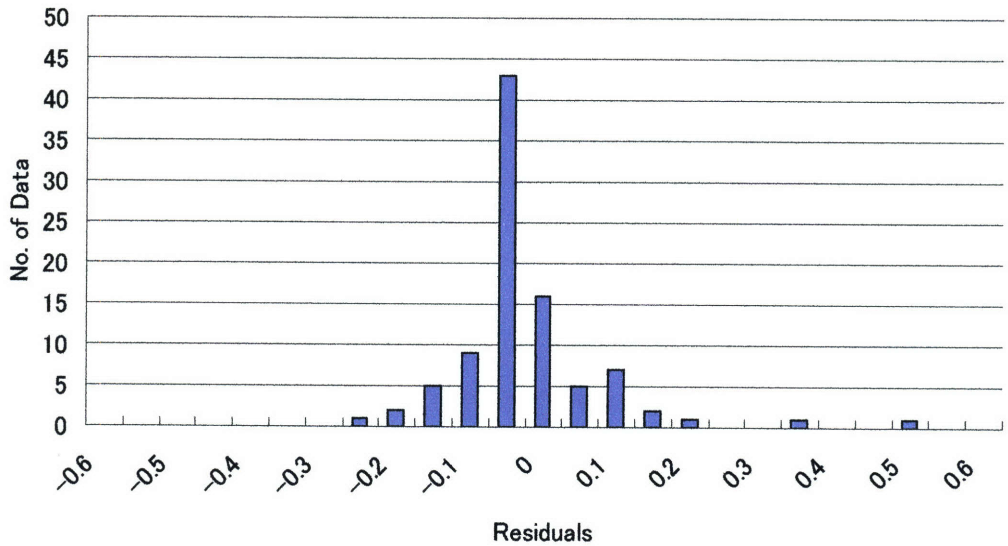


Figure 2-17: Distribution of Residuals of Recommended Consequence Model

(The Judgmental Extrapolation with $\Delta\alpha_2$=-2.5)

Because of the limitations of data, the recommended model is also adjustable if necessary to reflect new data.

2.4 Consequence Model for Collision with Incoming Train and for Train Fall after Derailment

We also developed a consequence model for collision of the derailed train with an incoming train (head-on collision) and for fall from significant heights.

The derailment consequence data used in the previous chapter include a few side intrusion cases for subway lines and trains falling from low heights. Hence this data set is not suitable for the present purpose and a more fundamental physical modeling approach must be used.

For head-on collision, we consider the reduced occupant space due to partial collapse of the train cars and the impact velocity of passengers who did not suffer critically by space reduction.

For the case of train falling from a viaduct, first we consider the effect of wall collision. If the train penetrates the wall, then the train is assumed to fall and collide with other obstacles. While other more complex scenarios could be envisioned, we view these sequences as representative to evaluate the consequences. In the case of falling, it is assumed that some cars could remain on the track, while others would fall.

The sequence of events considered for head-on collision and train fall are listed Table 2-9.

Table 2-9: Simplified Sequences to Calculate the Consequences

<table>
<tr><th></th><th>Head-on Collision</th><th colspan="2">Train Fall</th></tr>
<tr><td rowspan="2">Sub-Models</td><td rowspan="2">- Occupant volume loss
- Passenger impact</td><td colspan="2">- Secondary Accident (Discussed in § 2.2, 2.3)</td></tr>
<tr><td>Fallen cars</td><td>- Free fall
- Occupant volume loss
- Passenger impact</td></tr>
</table>

Simulation results reported by U.S. Department of Transportation (U.S. DOT, 1998) and SRI international (Klopp et al., 1996) were reviewed and the relationship between the damage in terms of Head Injury Criteria (HIC) or the loss of occupant volume and the train speed at which the collision occurs were considered. This was the basis for sub-models for occupant volume loss, passenger impact, and the free fall effects. The collision and the train fall models are obtained by combining these sub-models.

Collision Model

Because head-on collisions following derailments can be very complicated and variable events, it is difficult to develop consequence model for them using only empirical data. In this case, valuable information comes from simulation results. The crashworthiness of train cars and the occupant survivability have been extensively researched (Prasad et al., 1985), (U.S. DOT, 1998), (NHTSA, 2000), etc. The crashworthiness explains how the occupant volume is reduced by head-on collision while the occupant survivability indicates how safe the inside of a vehicle is when a collision occurs. Many of the simulations were made under limited conditions, e.g. in terms of train speed and train characteristics. A report by U.S. Department of Transportation (U.S. DOT, 1998) compares results for the conditions listed in Table 2-10:

Table 2-10: Choices of Simulation Conditions

Relative Train Speed [mph] (Km/h)	35 (56.3),	70 (112.7),	110 (177.0),	140 (225.3)		
Vehicle Design	Conventional,	Crush-Energy Management				
Car Type	Power car,	1st Class,	Coach,	Food car,	Cab car,	Commuter

In the DOT report, they simulated the risk for several sets of combination of car types. For example, one set of combinations has power car as the first car followed by six coach cars. There is one applicable set of car type combinations for Shinkansen trains. In the combination, a cab car is the first car followed by coach cars. The numerical simulation yield the occupant volume lost in each car and the secondary impact velocity of passengers. We used this set of results to quantify the consequences of head-on collision or train falling from high places. Both consequences depend on train speed.

Occupant Space Lost and Secondary Impact Velocity

Following the above-quoted DOT report, we estimate the consequences of head-on collision and train fall in two steps. The first step considers the loss of the occupant volume and the second step evaluates the losses from the secondary impact of passengers.

If the collision force exceeds the strength of the train structure, plastic deformation occurs and the occupant space is reduced, possibly causing injuries and fatalities. Even if the occupant space can be maintained, passengers in that space may be subjected to significant impacts.

The Occupant Space Lost

In the DOT study, the occupant volume loss was estimated the lumped mass model in Figure 2-18. The springs have non-linear force/deformation characteristics. Collision into an ideal rigid wall was considered, and the results were taken as representative train-to-identical train collision events. The relative train speeds in the DOT report are equivalent to a train colliding with an ideal rigid wall at half speed.

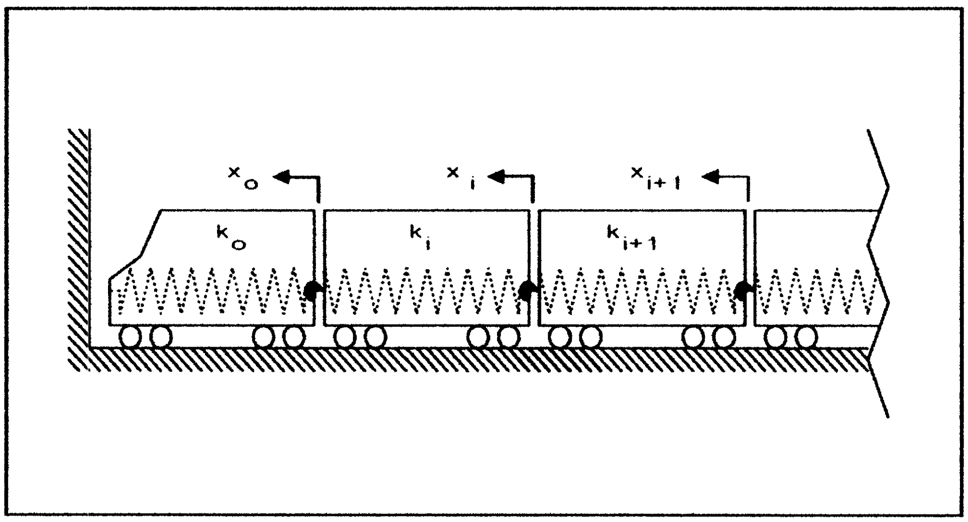


Figure 2-18: Lumped Mass Model Used in the U.S. DOT (1998) Study

Two train and 6 car types are examined in the DOT study. One of the car combinations, with a cab car as the first car (see Table 2-11), is comparable to the Shinkansen trains. The initial lengths of occupant space of each car are listed in Table 2-11 and the results of head-on collision are shown in Figure 2-19.

Table 2-11: Car Types and Initial Length of Occupant Space in the DOT simulation

Car Type		Initial Length of Occupant Space [m]	
		Conventional	Crush-Energy Management
1st Car	Cab car	23.47	21.95
Following Cars	Coach	23.47	17.85

Note that Crush-Energy management trains have crushable zones that can absorb the collision force before the force is transferred to the occupant space.

Relative Speed to the Oncoming Train

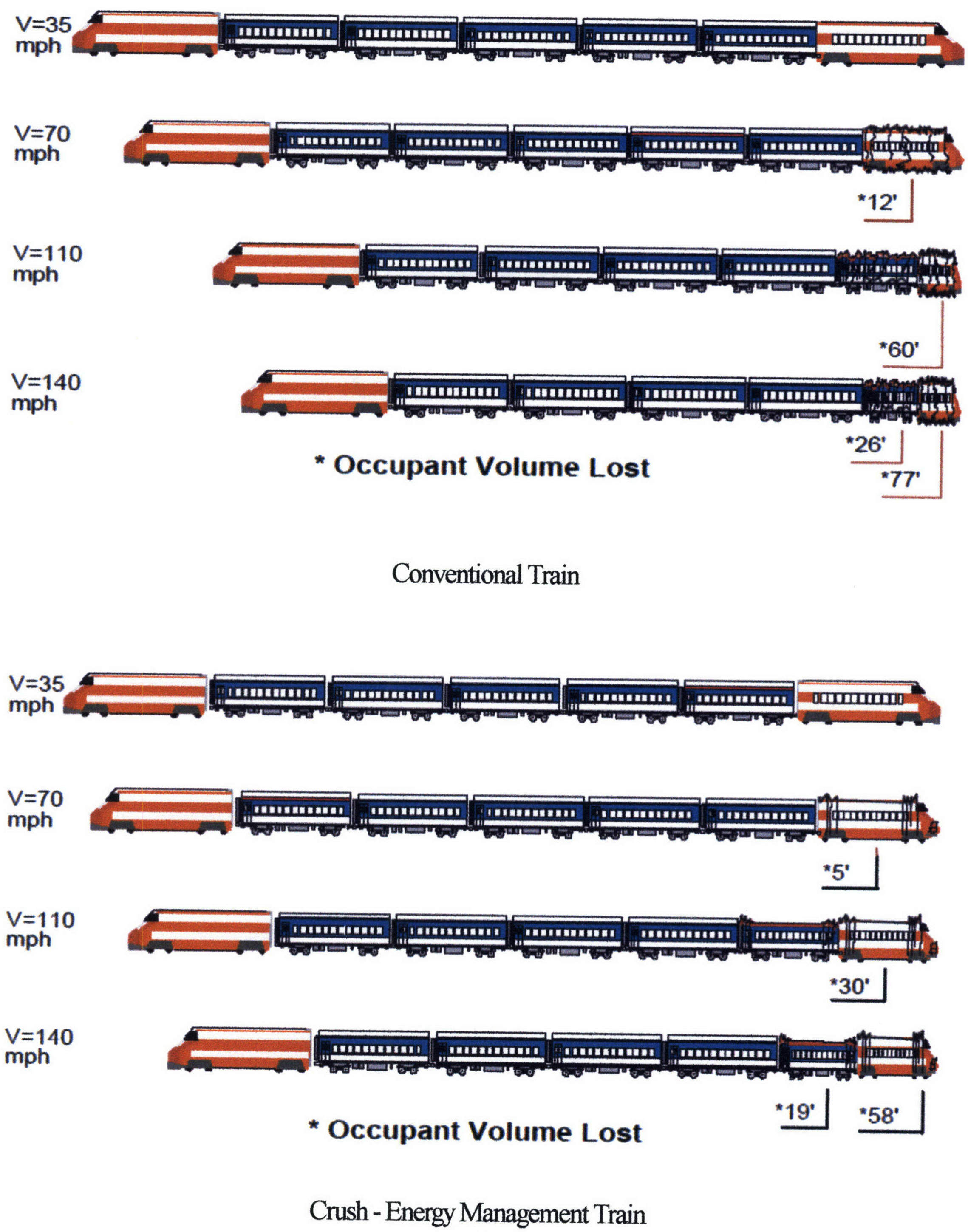
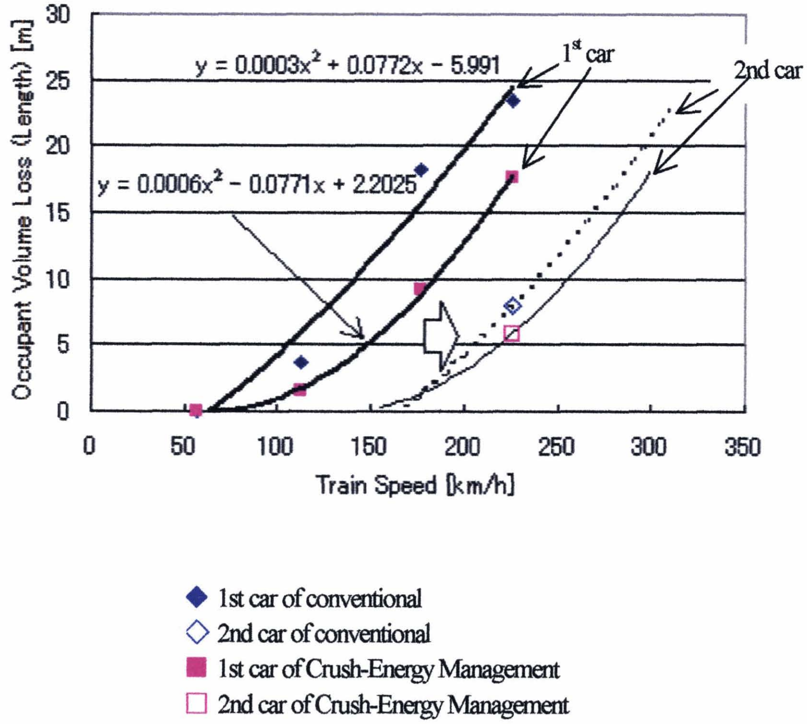


Figure 2-19: The Simulation Results of Occupant Volume Lost (U.S. DOT, 1998). Occupant Volume Lost is shown in Inch

The reduction in occupant space increases as train speed increases. In a 140 mph collision, the occupant volume of the second car is lost in both the conventional and crash-energy management trains. Collision energy is first absorbed by the lead car. What is not absorbed contributes to deformation of the following cars.

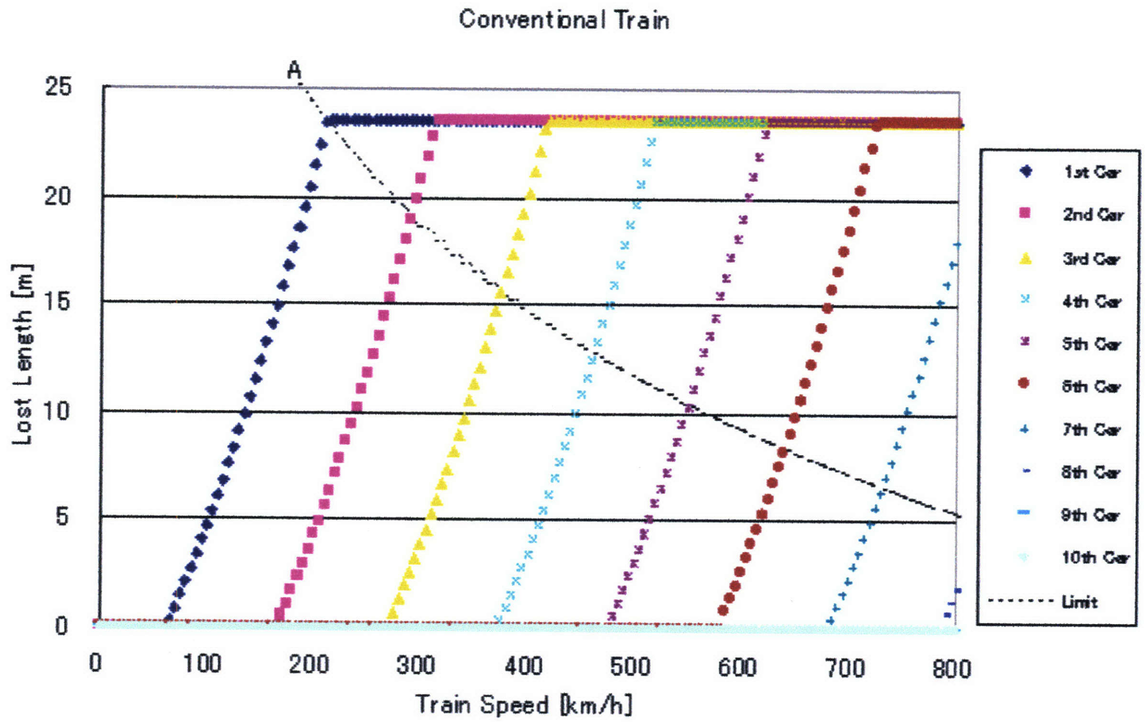
Figure 2-20 plots the total occupant volume loss as a function of train speed for the first and the second cars of conventional and crush-energy management cars. Figure 2-20 also shows quadratic functions fitted by least squares to the DOT data. It is assumed that the energy of the collision is transferred from leading car to following car, and the occupant volume loss is also occurred in this order without energy loss. By this assumption, the fitting of the first car's occupant volume loss can be projected to the second car. Under the same assumption, we can get the reduced occupant volume for each train can be obtained. (See Figure 2-21)

In reality, it is very rare for a train to remain straight as it collides into another train. If consecutive cars are not aligned, the transmitted force by the leading car is reduced. Lines A and B in Figure 2-21 show a plausible upper limit to the volume loss of different cars. According to these lines, the maximum reduced volume of the 1^{st} car is 100%, whereas that of the 10^{th} car is only 0.1%.



Vehicle Design	Fitted Equation
Conventional	$y=0.0003x^2+0.0772x-5.991$
Energy Management	$y=0.0006x^2-0.0771x+2.2025$

Figure 2-20: Simulation Results of Occupant Volume Loss with Fitted Analytical Expressions



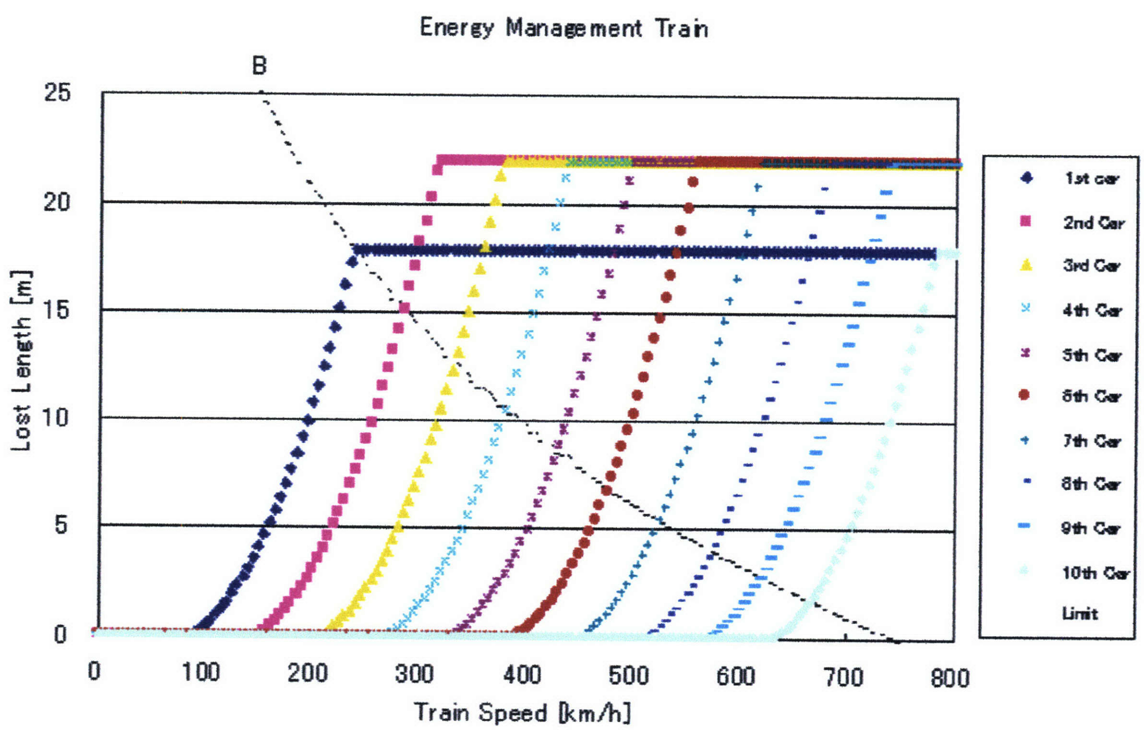


Figure 2-21: Reduced Occupant Volume for Each Car.

when A and B show the assumued maximum volume loss for different cars.

In our analysis, we have considered a train has 10 cars and seat parameters such as the number and position of seats listed in Table 2-12. These characteristics are representative Shinkansen trains. If the train speed at the time of accident is obtained, the occupant volume loss of each train can be calculated from Figure 2-21. Considering the seat parameters for each car, the number of fatalities for each car can be calculated, and the total number of fatalities of entire train is also calculated by summation of them. Because there are differences of the total number of seats between conventional car and crush-energy management car, we calculate the ratio of occupant loss. (See Figure 2-22)

Because of the limitation of the occupant loss that we set (A and B lines in Figure 2-21), the fatality ratios of both cars increase as the train speed increases moderately, not rapid. The ratio of both conventional and crush-energy management cars have similar tendency, although that of crush-energy management is lower than that of conventional at all speed region. In addition, the fatality rate of crush-energy management starts to rise at around 180km/h, while that of conventional car stars at around 130km/h. It is indicated that the crush-energy management structure is slightly effective rather than the conventional structure.

Table 2-12: Seat Parameters (Simulate the Shinkansen Train)

	Cab car	Coach
Row number	13	18
Seat No. in a row	5	
Passenger number	66 (Incl. driver and conductor)	90
Total (10 cars) (2 cabs and 8 coaches)	852	
Seat pitch	0.98	
Cab seat position	3[m] from the head	—
Cab section length	7.8148[m] from the head	—

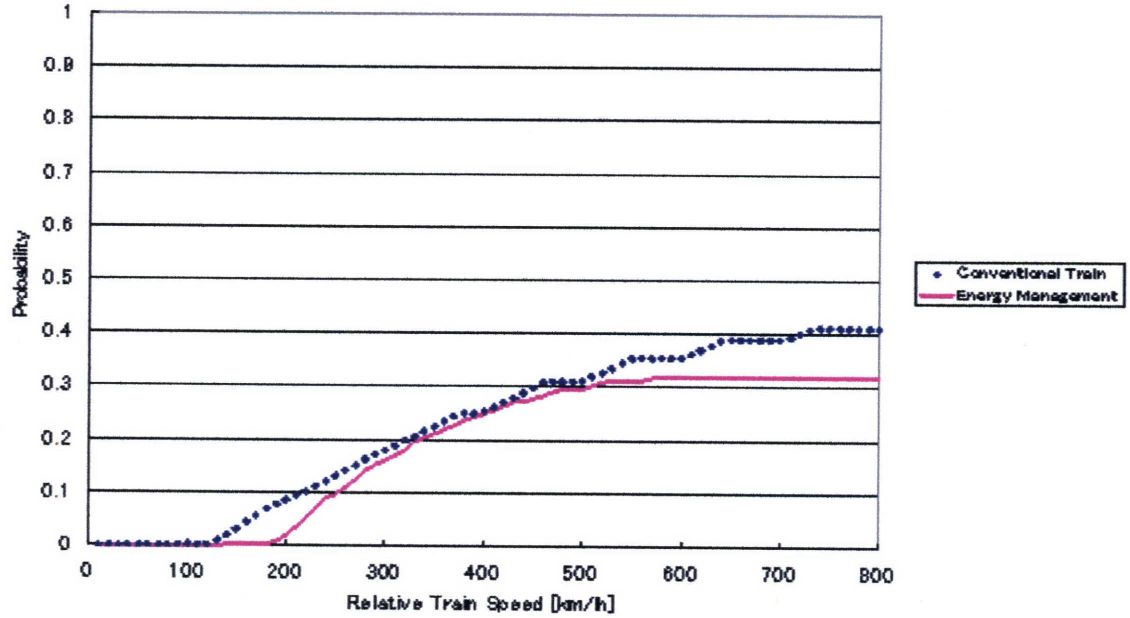


Figure 2-22: Fatality Ratio by Occupant Volume Loss

Secondary Passenger Impact and Its Consequences

Another case of casualties and fatalities is the secondary impact of passengers with the seats in front of them. The consequences of there events depend on the secondary impact velocity.

To estimate the secondary impact velocities, it was assumed that seats are forward-facing and arranged in consecutive rows, as in the DOT report. The distance between the occupant's nose and the seat ahead of him/her was assumed to be 2.5 feet (0.762m), the seat pitch was assumed to be 42 inches (1.067m), and an occupant's head was assumed to be 8-inches deep. Note that this seat pitch is longer than that of the Shinkansen. (see Table 2-12) The secondary impact velocity is the velocity of the occupant relative to the train just before the occupant contacts an interior surface (U.S. DOT, 1993). (Figure 2-23) Shorter seat pitch lengths produce smaller secondary impact velocities. Since real situations are usually more complex, and can be envision more severe cases. Therefore, we use the results of DOT for more severe cases.

The secondary impact velocities estimated by the DOT are shown in Figure 2-24. The results for the last car, the power car, should not be considered, because a power car is not used in the Shinkansen system. The secondary Impact velocities in a Crash-Energy Management Design train increase with the car number after the 3rd coach, likely due to the force of the last heavy power car. To eliminate the effect, we did not use the 5th car's data.

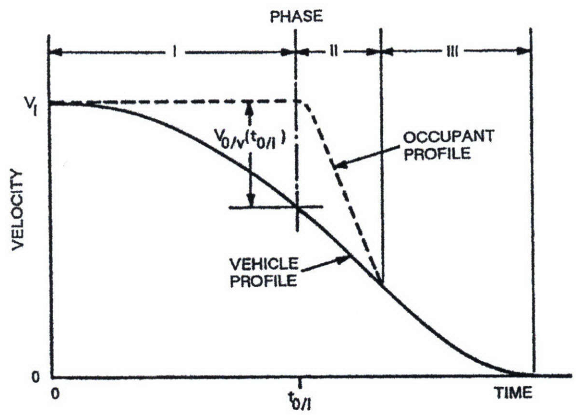
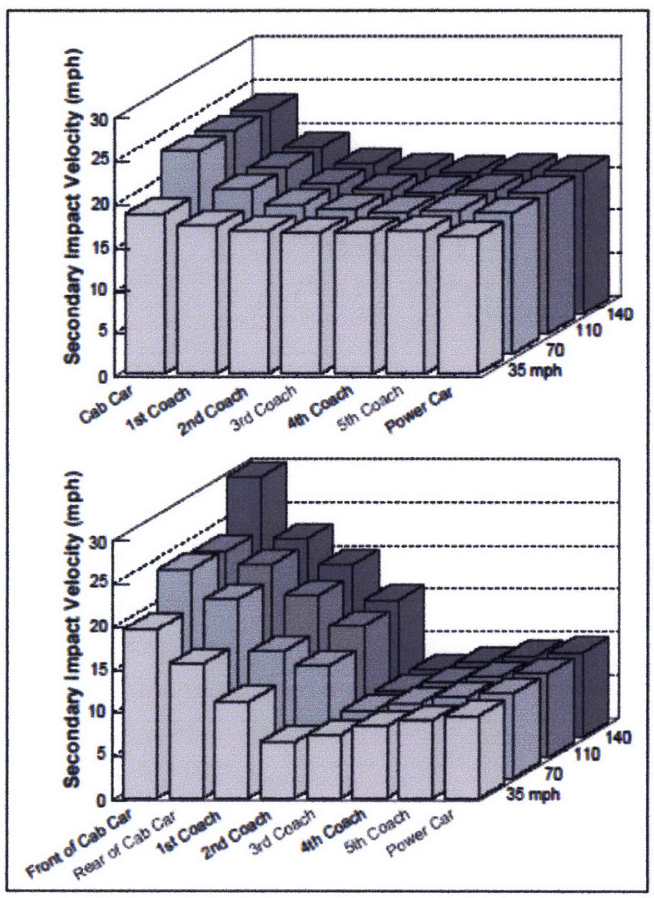


Figure 2-23: The Secondary Impact Velocity on a Occupant: $V_{o/v(to/i)}$ (DOT, 1993)



Note: Conventional Design (top), Crash-Energy Management Design (bottom)

Figure 2-24: Occupant Secondary Impact Velocities (Cab-to-Cab Car Collision) (DOT, 1998)

The consequences of passenger impacts have been studied separately for head, chest, spinal, and abdominal injuries. Among these criteria, especially, Head Injury Criteria (HIC) are used most often to evaluate test and simulation data, because head injuries are the most life-threatening ones (McHenry et al. 2004). The HIC Curve that relates the fatality rate to head injury severity was introduced by U.S. ISO delegation. (Prasad et al, 1985) Recently a new criterion, HIC-15, are used to evaluate the occupant protection such as seat belts and airbags instead of ordinal HIC (HIC-36). The HIC-15 is calculated in less duration of 15ms, than that of the former HIC, 36ms. The injury criteria for the HIC-15 in Table 2-13 were set under the provision of the U.S. advanced airbag regulation (National Highway Traffic Safety Administration (NHTSA), 2000).

Table 2-13: Criteria for HIC-15

	Acceptable	Marginal	Poor
HIC-15	560	700	840

Here, "Acceptable" is interpreted as synonymous the criterion of "Minor injury", "Marginal" of "Serious injury", and "Poor" of "Fatal". Keeping the relationship of these criteria at 50% of casualty and fatality rates, the HIC curve is project to the curves of Minor and Serious injury rates. As indicated in Figure 2-25, the differences between curves are ratio of minor and serious injuries, and fatality

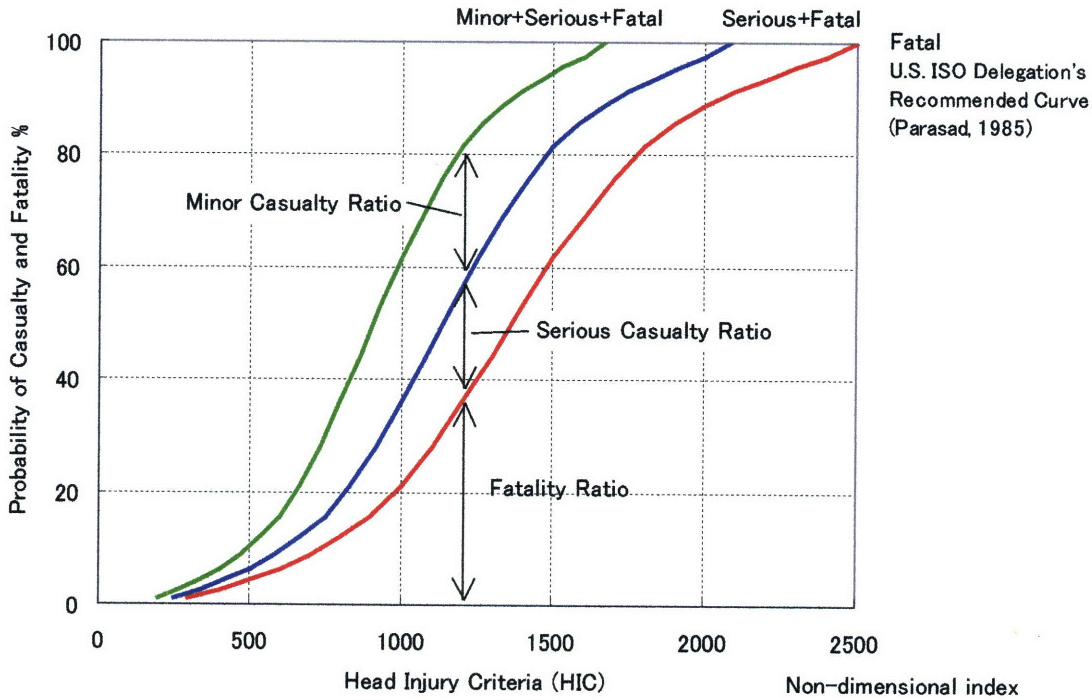


Figure 2-25: Casualty and Fatality Rates as a function of HIC

The HIC value depends in part on the type of seats used. The types considered how the back force/deflection characteristics described in the National Highway Traffic Safety Administration (NHTSA) Standard (Figure 2-26). The softer seat is used in high-speed trains and the stiffer ones are used in commuter trains. The padding on the seat is assumed to be 4 inches (0.102m).

The extreme cases of whereas elastic and elasto-plastic seats were considered for each seat type. In the elastic extreme, the occupant body is subjected to a fully rebound force. In the elasto-plastic extreme, the energy is absorbed by the seat deflection. In the U.S. DOT report also reported the HIC curve as a function of secondary impact velocity for the seat characteristics described above (Figure 2-27). From this figure, we looked for quadratic equations that can fit lines of elastic and elasto-plastic seats characteristics of high speed train. These equations can indicate the relationship between secondary impact velocity and the HIC.

The results of numerical simulation by U.S. DOT about the occupant secondary impact velocities when a cab-to-cab car collision occurs are shown in Figure 2-24, and plotted secondary impact velocity of these results are shown in Figure 2-28. This figure can show the relationship between secondary impact velocity and relative train speed. Referring the HIC curve that we re-defined for three severity, minor injury, serious injury, and fatality in Figure 2-25, the casualty and fatality rates as a function of the relative train speed for each car can be estimated.(Figures 2-29 and 2-30)

By combining the fatalities due to occupant volume lost and fatalities and casualties due to secondary impact, overall casualty and fatality rates for a entire train can be estimated in Figures 2-29, 2-30 and 2-31.

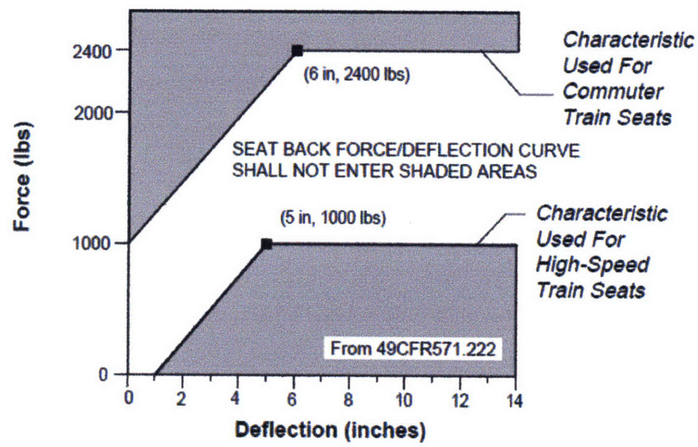


Figure 2-26: Seat Back Force/Deflection Characteristics (U.S.DOT, 1998)

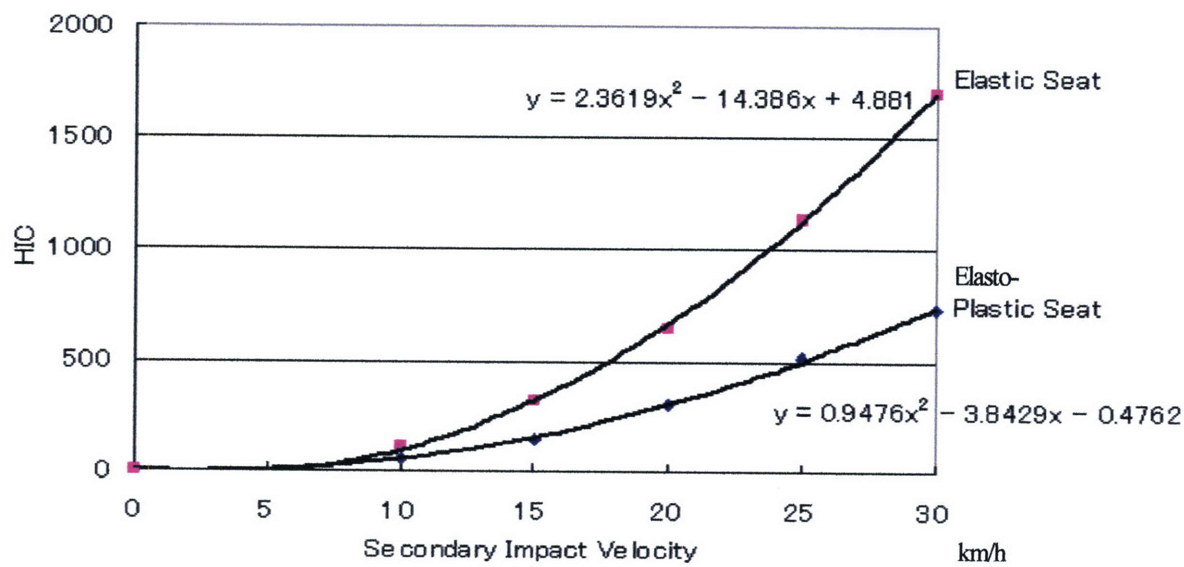
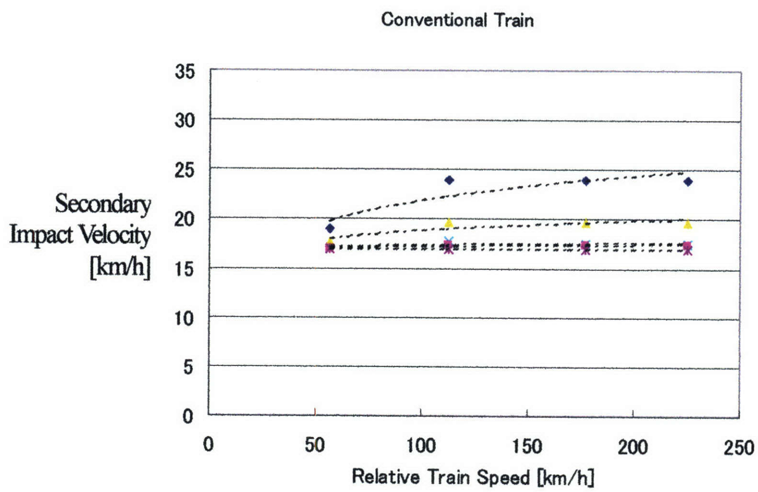
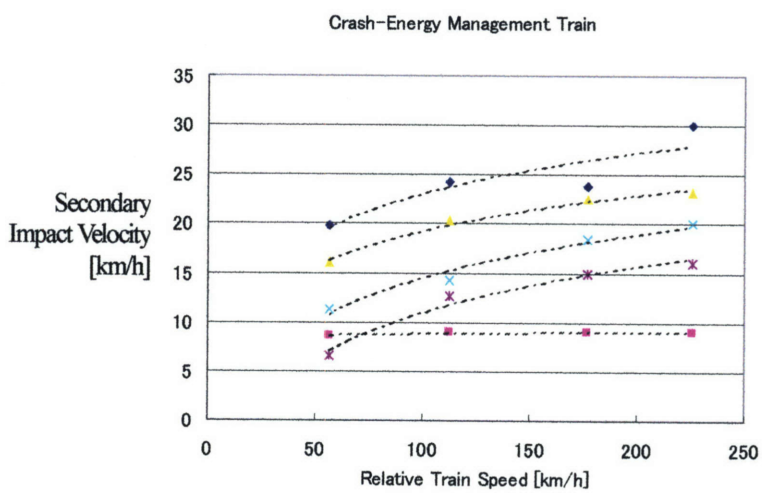


Figure 2-27: Head Injury Criteria as a Function of Secondary Impact Velocity



1st Car (Cab)	y = 3.6178Ln(x) + 5.2494
2nd Car	y = 1.4471Ln(x) + 12.2
3rd Car	y = 0.3314Ln(x) + 15.847
4th Car	y = 0.2894Ln(x) + 15.9
5th Car	y = 17



1st Car (Cab)	y = 6.0822Ln(x) - 4.9715
2nd Car	y = 5.2908Ln(x) - 5.0934
3rd Car	y = 6.4529Ln(x) - 15.202
4th Car	y = 6.832Ln(x) - 20.473
5th Car	y = 0.2894Ln(x) + 7.5

Figure 2-28: Extrapolated Lines of HIC as a Function of Relative Train Speed

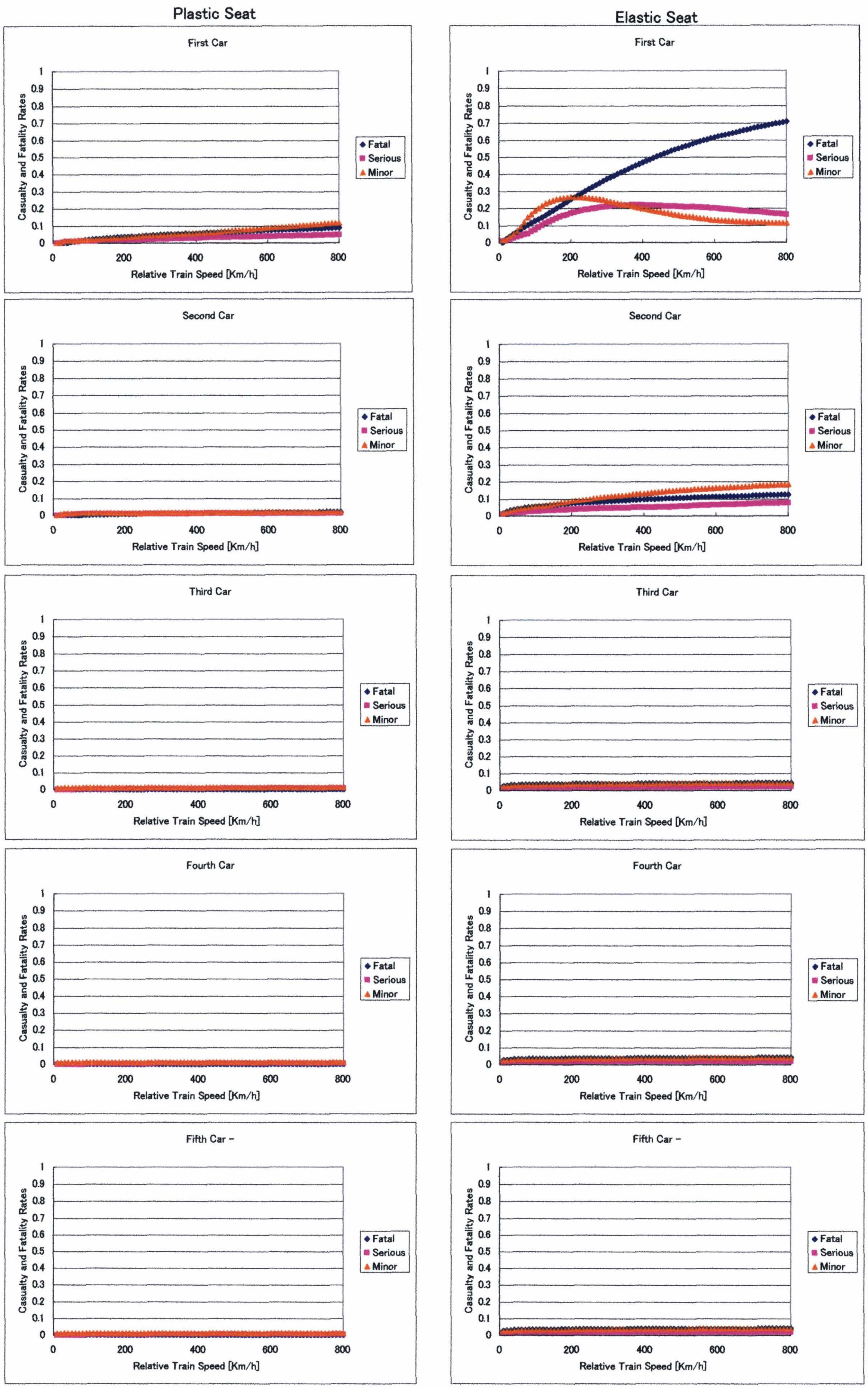


Figure 2-29: Casualty Rate by Secondary Impact(Conventional Train)

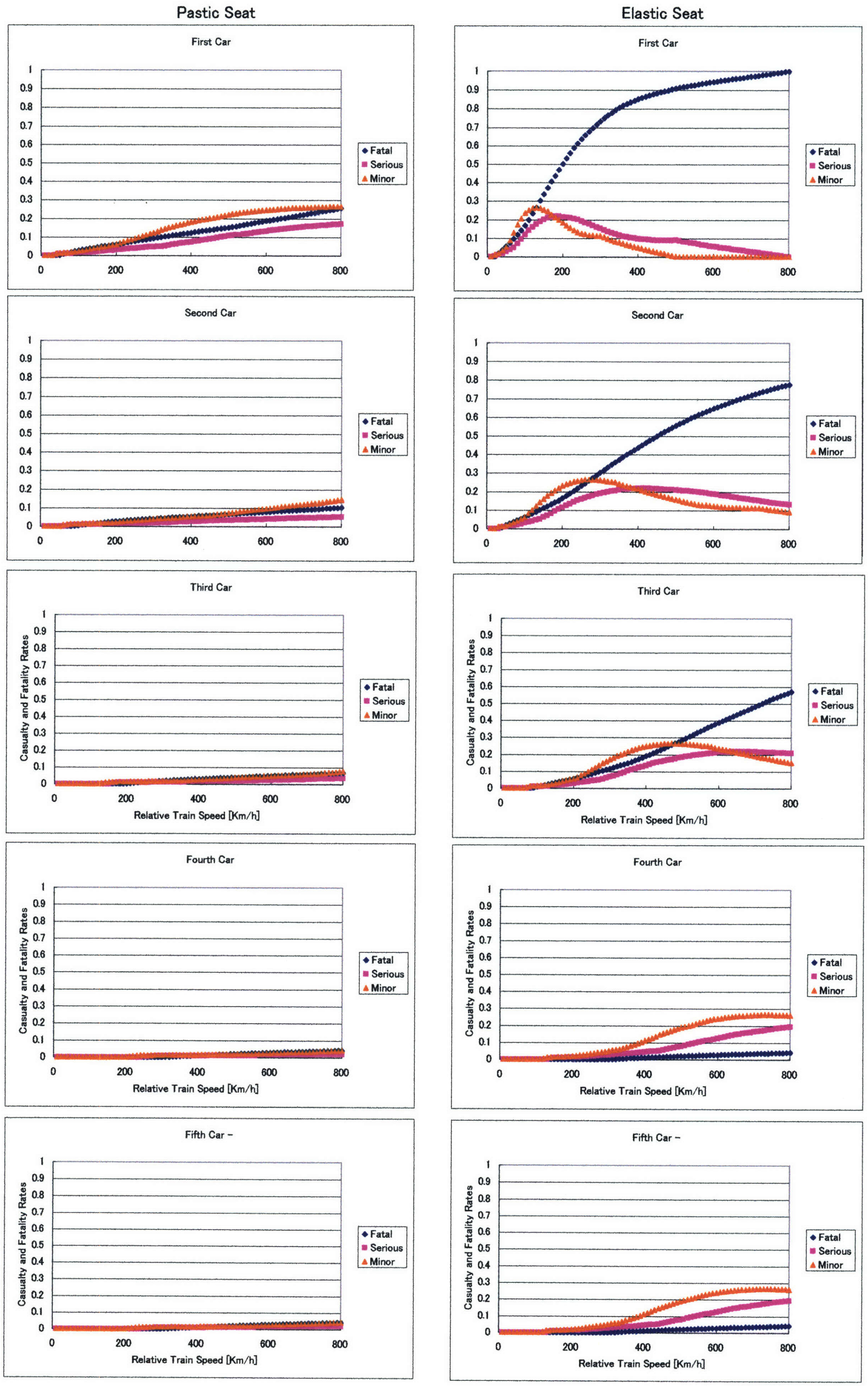


Figure 2-30: Casualty Rate by Secondary Impact(Crush-Energy Management Train)

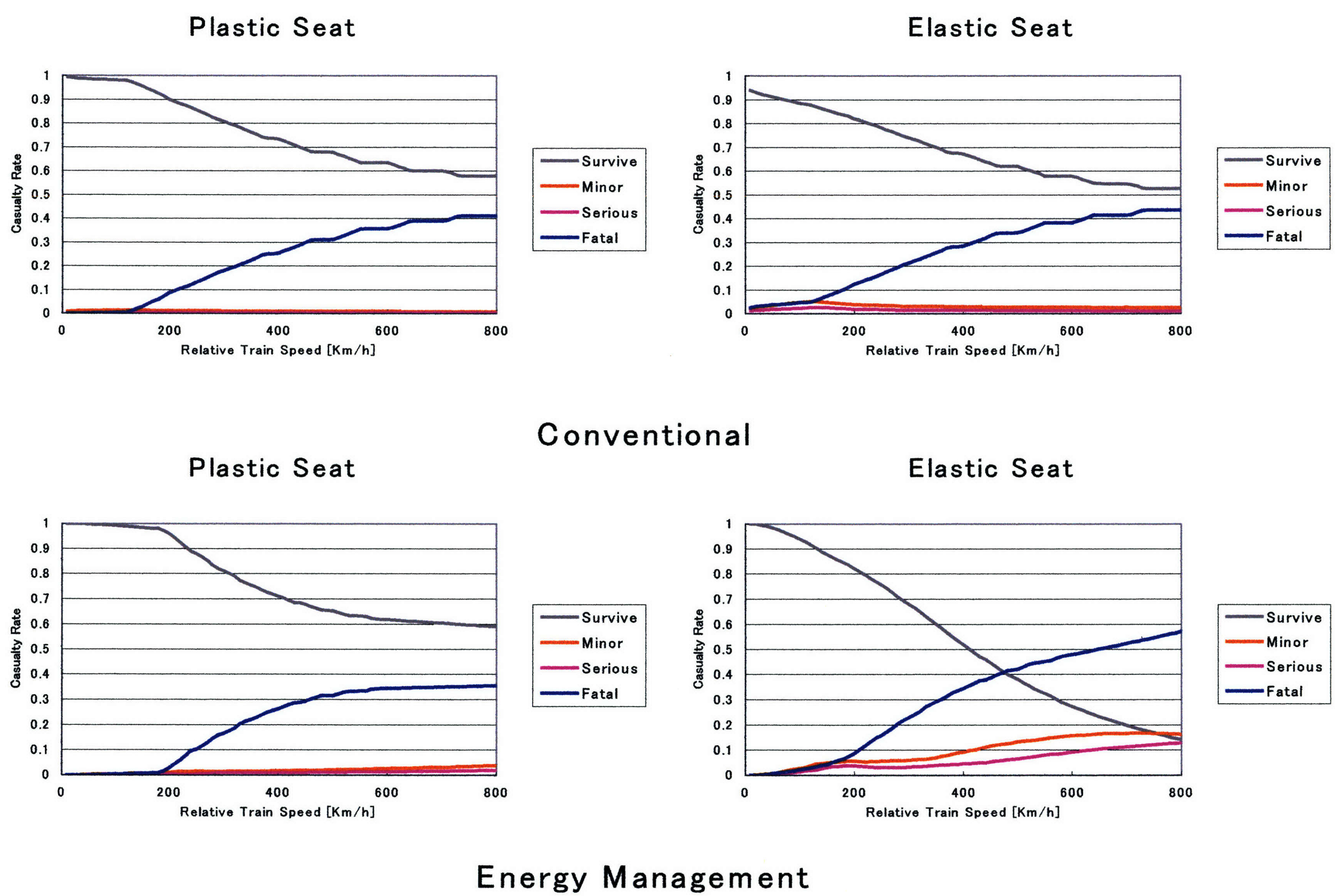


Figure 2-31: Overall Casualty and Fatality Rates of the Head-On Collision (10 cars)

From these results, one can see the fatality rate is drastically increasing with relative train speed. On the contrary, the casualty ratios are almost flat except one result (Energy Management with elastic seats). Although there are the difference between normal speed and relative speed, if we assume that a train collides with a rigid wall, train speed of the results can be transferred as half of relative speed. Comparing with the results of "Derailment on Own Track Model" that is explained in §2.3, the minor and serious injury ratios of the head-on collision model are smaller than that, while the fatality ratio has similar tendencies. In fact, the casualties and fatalities due to the head-on collision should be larger than that of the previous model. These small issues are affected by the fitting of the numerical simulation results reported by the U.S.DOT.

In addition, consequences in the development of the "Derailment on Own Track Model" were considered in a unit of a train, not each of cars. The differences of cars might be needed to be considered.

Falling Model

Situations when a train falls from a significant height can be complicated to analyze. Here we simplify the event sequence of such accidents to obtain first estimates of casualty and fatality rates for the case of Shinkansen train running on a viaduct or bridge..

First, collision with a wall of the viaduct occurs. Second, some cars fall from the viaduct to the ground. After that, the fallen cars collide with various obstacles. The speed at which the fallen cars collide may be high. In our analysis, we assume that fallen cars suffer from the impact individually while at the high speed, because there is no support such as tracks or walls when the train falls down from the viaduct. The first step can be expressed by the previous model, the "derailment on own track model" The final step also can be represented by two sub-models that we discussed former section. One is the occupant volume lost, and the other is the impact on the passenger's body. The phenomenon of free fall, however, should be estimated by another sub-model.

Train falls were considered by SRI International (Klopp et al., 1996). In particular, SRI International estimated HIC values for a high-speed train similar to the Shinkansen falling from three different heights (1, 3 and 6 meters). The HIC value obtained by HIC are 41, 142, and 340, respectively. Using these results, a relation between heights of fall and HIC can be estimated, as shown Figure 2-32.

Assuming that the train has 10 cars of which 5 fall from a 10 meters viaduct, we simulated the casualty and fatality rates as a function of relative train speed. (Figure 2-33)

From the results, one can see the curve of fatality rate is winded at around 100 km/h. This is because of the plausible upper limit to the volume loss defined in the previous section. (See Figure 2-20) The fatalities skyrocket until 100 km/h caused by the occupant space lost. After the ratio reaches the limit, the fatalities increases by only secondary passenger impact. Minor injuries increase until around 50 km/h, and then turn to decreasing. This is caused by the radical increase of minor injury ratio for the HIC that defined in Figure 2-25.

Comparing the results of "Derailment on Own Track Model" that is explained in § 2.3, Fatality ratio in the falling Model is much larger than that of the former model. Because of the limitation of actual data, we should aware of the existence of uncertainties, but the trend that the consequence of train fall is much severe than that of other accidents is convincing.

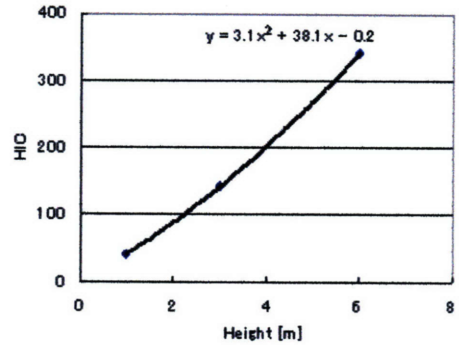


Figure 2-32: HIC as a function of Heights of Falling

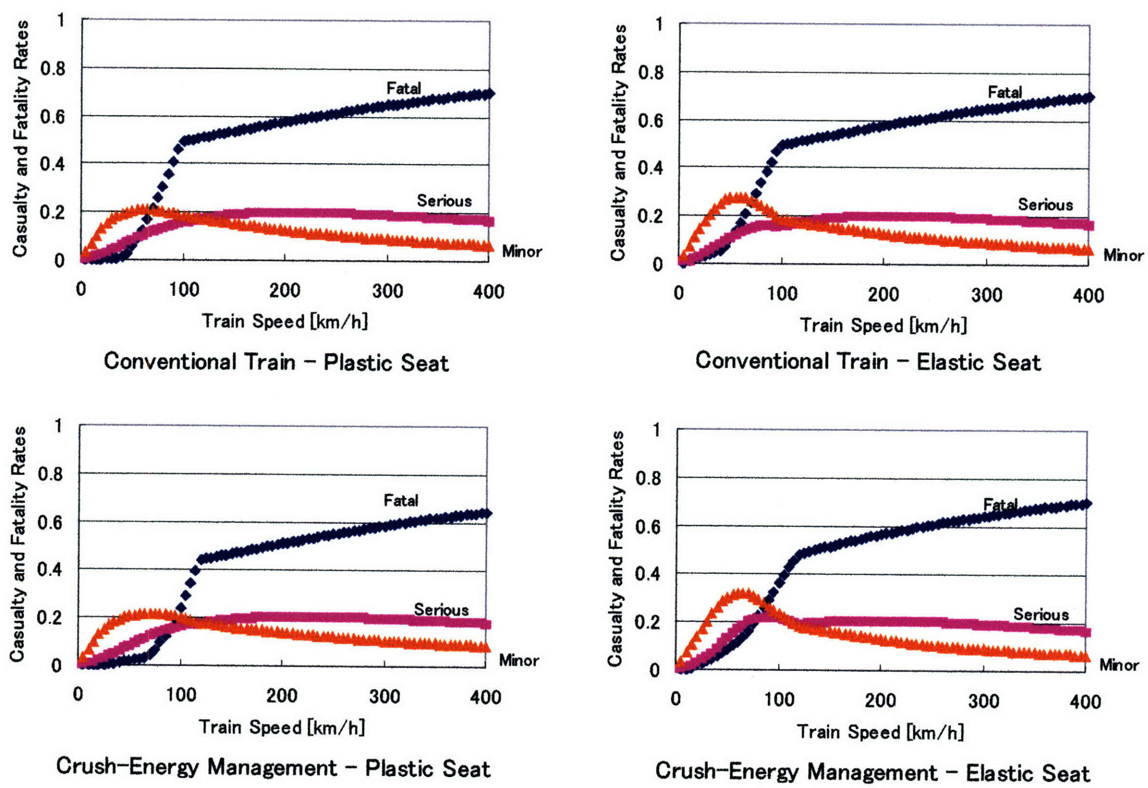


Figure 2-33: Casualty and Fatality Rates due to train fall

The train has 10 cars of which five fall from a 10-meter high viaduct

2.5 Conclusions on the Consequence Model

We have developed a consequence model for train derailment in terms of passenger casualty and fatality rates. The model consists of two sub-models. The first sub-model is for the case when the train remains in its own track. In this case, the consequence relations are estimated from accident data. The other sub-model considers head-on collision and train fall was developed using available numerical simulation results.

The "Derailment on Own Track Model"

The first sub-model uses a linear logistic model of various casualty and fatality rates. The model is fitted by least squares or weighted least squares to derailment data.

- To quantify the consequences of derailment, we introduced a linear logistic model with the Logit and used least squares or weighted least squares to fit the derailment consequence data that compiled by SRI International. To identify the simplest suitable model structure, we used stepwise regression and statistical hypothesis testing. As a result of these approaches, we found the X_{severe} indicator valuable can be used to reliably estimate the model instead of precise parameters.
- Using methodologies that are described above, we could show the relationship between train speed and casualty and fatality rates for two types of accident severities, as defined as the secondary accident and no secondary accident, in each casualty category, as defined as minor, serious and fatal. The results that are obtained by various methodologies have similar tendency. In the case of derailment without secondary accidents, the casualty and fatality rates increase with increasing train speed and do not cross. In the case of secondary accidents, serious injuries and fatalities increase more drastically than the previous case, in contrast, minor injuries decreases at high speed region. From these results, we selected one as a recommendable model that the highest total casualty and high fatality ratio as a extreme

model.

- To obtain a suitable model under the condition of limitation data, we considered some methodologies of data analysis such as the setting of the substitution valuables for originally zero value and weighted least squares. In addition, SRI database does not include head-on collision with incoming train and train fall from high height. In order to consider the railway network including Shinkansen system, we should consider the consequences due to these accidents. Therefore, we developed another sub-model, "Head-on Collision and Train Fall".

Head-on Collision and Train Fall Model

Combining sub-models that extracted from applicable numerical simulation results, we developed the Head-on Collision model and Train Fall model. Because of the two different characteristics of seats and two types of train structure, four types of results are obtained for each sub-model. The curves of these results are not smooth, because the consequences are considered not for an entire train but for each of cars and are gather them up.

To estimate the consequences of head-on collision and train falls, some simplifying assumption were made.

- **Head-on Collision**

For head-on collision, we assume that the reduced occupant space due to partial collapse of the train cars occurs first, and then secondary impact velocity subject to passengers who did not suffer critically by space reduction. We also assumed that the collision power is transferred from leading train to following train.

In terms of the reduced occupant space, the simulation results of the occupant space loss as a function of relative train speed, which was reported by U.S. DOT, were fitted and the ratio of fatalities caused by the lost was obtained. In the sub-model of the impact on the passenger body, the relationship between the head injury criteria (HIC) and the relative train speed were also obtained from the report. Applying the recommended HIC curve and estimated casualty HIC curves that can indicate the fatality and casualty ratios as a function of HIC, we can calculate the probability of casualty and fatality if we can get speeds of the train and an incoming train. The fatalities due to the reduced occupant space and the fatalities and casualties due to the impact on the passenger body are considered for each of cars.

In the results, the fatality rate is drastically increasing with relative train speed. On the contrary, the casualty ratios are almost flat except one result (Crush-energy management structure with elastic seats). Comparing with the results of "Derailment on Own Track Model", the minor and serious injury ratios of head-on collision are relatively smaller than that of "Derailment on Own Track Model" In reality, the casualties and fatalities due to the head-on collision should be larger than that of "Derailment on Own Track Model". The smaller casualties in the head-on collision model is because only fatality rates are considered in the reduced occupant space sub-model, and the head-on collision model is applied not for entire train first but for each train, in contrast with the Derailment on Own Track Model in which the consequences are considered for an entire train unit.

- **Train Fall**

For the case of train fall from a viaduct, we assumed simplified sequences, although the actual accidents should be more complex. First, a wall collision whose consequences can be calculated by the model of "Derailment on Own Track Model " is considered. After the collision with a wall, the some cars of the train are assumed to fall and collide with other obstacles. It is also assumed that remains could stay on the track.

These steps can be explained by the sub-models of the occupant volume loss, the second impact on the passenger body, the free fall, and the collision with some obstacles. The Free fall was examined by the SRI International, and it also can be transferred as a sub-model.

Comparing the results of "Derailment on Own Track Model", Fatality ratio in the Falling model is larger than that of the former model. The trends, which the consequence of train fall is much severe than that of other accidents, are convincing.

In these consequence models explained above, only the expected consequences are considered. In order to estimate the derailment risk as realistic results, the uncertainty such as the distribution and the variances of the consequences should be dealt with.

The occurrences that obtained in this chapter will be used as the principal probabilities to estimate the probability of possible scenarios in "Regional Approach".

3 Regional Approach to Earthquake Risk for Train Derailment

In this chapter, we describe a regional risk analysis approach for the derailment of high speed trains. The regional risk analysis approach can analyze the simultaneous derailment risk for the whole Shinkansen network. The "Shinkansen Earthquake Impact Assessment System" (Shimamura et al., 2006) can analyze the risk only segment by segment under the assumption that the segment has a train running in it. In the JR East system, segments correspond to electrical sections of a line and are 30 to 50 km long. The current system assumes that the segment consists of one viaduct structure. In reality, there are many trains in the Shinkansen network during operating time, and conditions vary along the track, even within a segment. 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 exemplify, we focus on the Tohoku Shinkansen line. In the program that implements the regional approach, we used the actual timetable and track conditions of the Tohoku Shinkansen line. We calculate not only the probability of derailment but also the consequences of derailment events.

We explain the regional approach in the following order;

- Calculation flow of the program
- Application for the Tohoku Shinkansen line
- Demonstration of the calculation and the results

3.1 Calculating Flow and Methodology

First, we explain the flow chart of the program for the regional approach. The program consists of four parts. In the first part, the date and time of the earthquake, its magnitude and epicentral location, the train locations and conditions, relevant early-warning seismographs and track conditions at the train locations are selected. The second part calculates the probability of all possible derailment scenarios. In the third, a scenario is selected, and in the fourth part, the consequences are calculated. Derailment probabilities are currently calculated using the JR East approach. In the future, this approach will be updated using a method that is being developed in parallel with this research. The flow of calculation is shown in Figure 3-1.

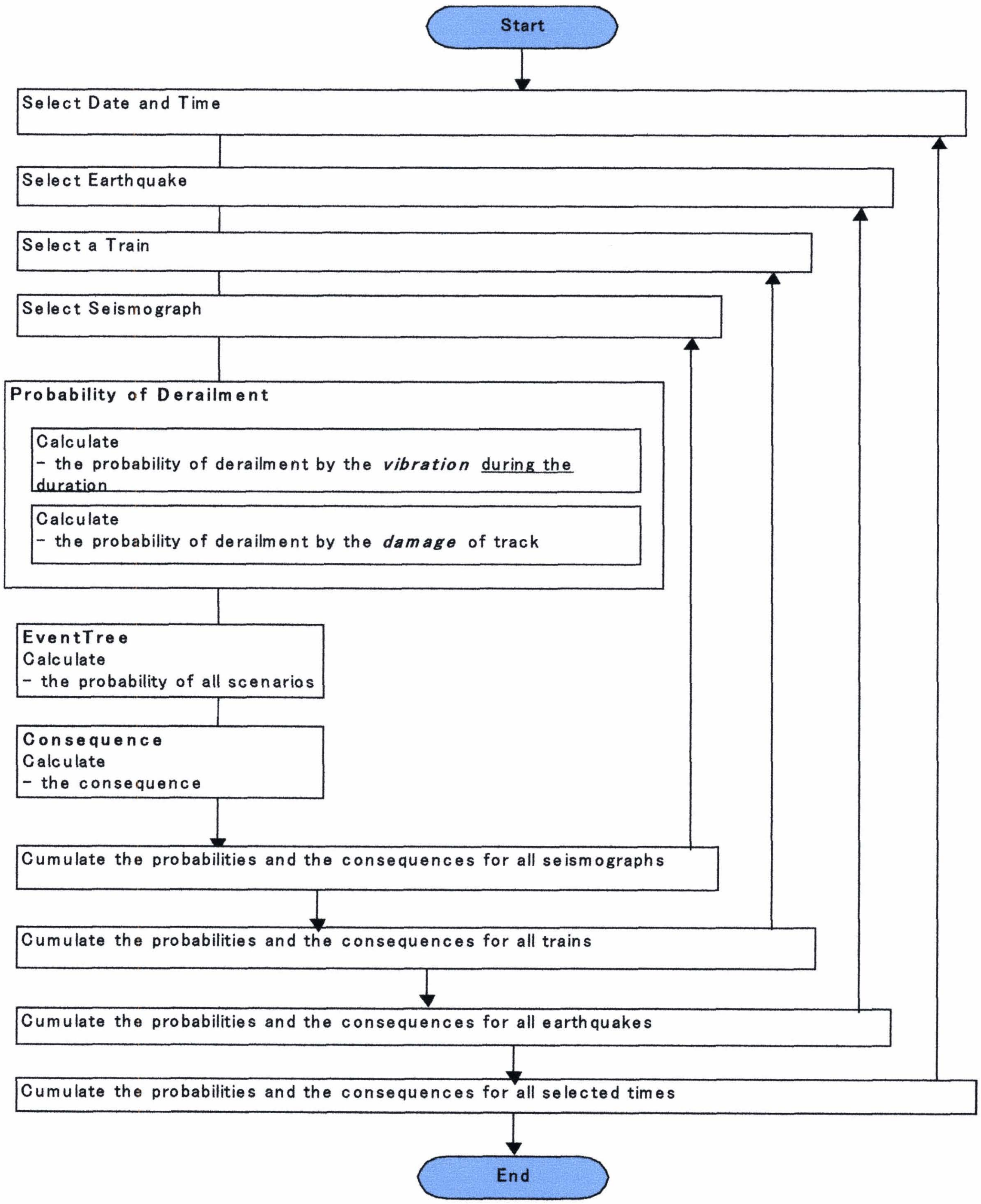


Figure 3-1: The Calculating Flow

Select Date and time, Earthquake, Train, Seismographs, and Track Conditions

In the program, we use several databases to select alternative earthquake, train and track parameters. These include data on earthquakes, the train timetable, seismographs, and track conditions along objective railways.

- **Earthquake Data**

For a list of possible earthquakes, including hypocenter, magnitude, and annual frequency, we use the commercial seismic model RiskLink® which is also currently used by JR East. The earthquake database includes 49,282 events that cover all of Japan.

The S-wave and P-wave velocities are assumed to be 3.5 km/s and 6.0 km/s, respectively.

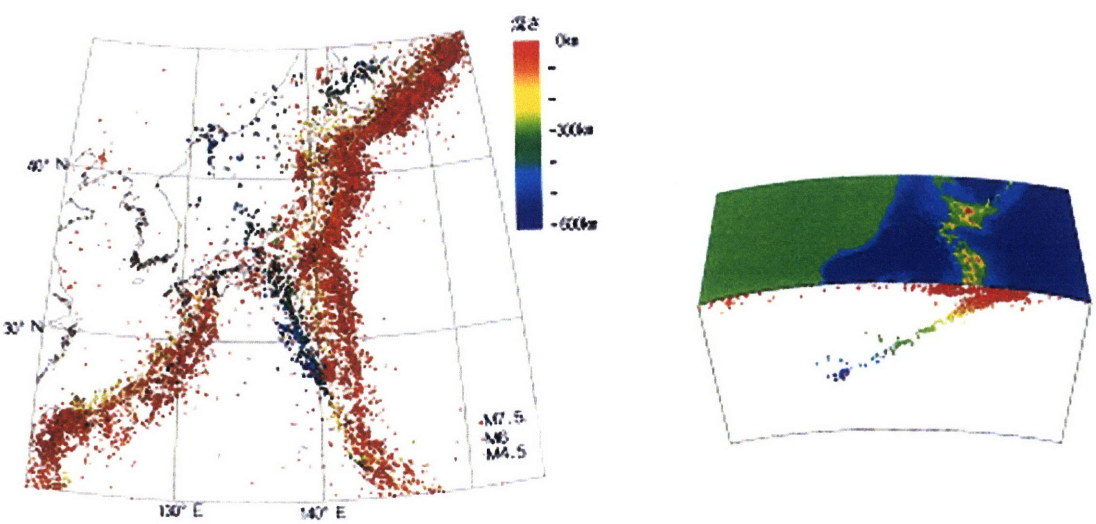


Figure 3-2: Epicenters Around Japan (RMS™, 2003)

- **Seismographs**

To issue alarms before the strong phase of the S waves arrive at the site of the trains, a seismic early warning system (SEWS) has been in operation since 1978. Since 1998, the Compact Urgent Earthquake Detection and Alarm System (Compact UrEDAS) has been used as a protocol to trigger the alarm. The compact UrEDAS measures the PI value that is the maximum of the inner product of the earthquake response acceleration α [gal = cm/s^2] and the earthquake response velocity v [kine = cm/s] for one second after the arrival of the P-wave.

$$PI = \max\left[\log|\alpha \times v|\right]^{1\,\mathrm{sec}} \qquad \text{3-1}$$

An alarm is issued if PI value exceeds 3. PI is non-dimention value.

The SEWS for the entire Shinkansen line includes two sets of accelerometers. One set is placed along the track (wayside system), and the other is placed along the eastern coast (coastal system). There exist 46 seismographs along the line and 15 seismographs along the coast in entire Shinkansen line, and 28 along the line and 13 along the cost in the Tohoku line. Each seismograph controls several segments of the line. If the PI value calculated at a seismograph exceeds the threshold value, an alarm is generated and the electricity to the trains is automatically shut down. In our program, the PI value can be estimated by an attenuation equation that is used in the current JR East system, as follows.

$$PI = 0.83M - \log(r+h) - 0.0098 \times 10^{-0.11M} r - 1.2 + \varepsilon \qquad \text{3-2}$$

where M[2] is the magnitude of the earthquake, *r* is the distance from the epicenter [km], and *h* is the depth of

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[2] The Japan Meteorological Agency magnitude

the hypocenter [km], and ε is the error function of the regression. The standard deviation of the error function ε is 0.45 that was found in previous research (NHTSA, 2000). In our program, this attenuation equation to calculate the PI value and the probability that the SEWS issues a warning.

- **Track conditions**

Available data are also used to assess the condition of the track at the train locations when an earthquake occurs.

In the JR East, there are several land registers for track maintenance and land administration. We use three of them: the register of tunnels, the register of bridges and the register of embankments. The registers give the start and end points of each type of structure. These points are recorded as distances from Tokyo Station. Some discrepancies exist between registers because of the use of different distance measurements. To combine them to one database, we have set an order of priority; first tunnels, then bridges, and finally embankments. In reality, most of the Tohoku Shinkansen line is on viaducts. Although some of the viaducts are included in the bridge register, most of them are not. Locations that are not registered as tunnels, bridges or embankments are considered to be viaducts. The combined database includes also additional information on embankments. The register of embankments differentiates between cut-off wall and slop. This is important for us because the consequences might be different in the case of intrusion into a wall and sliding on a slope. Soil condition data are also included in the combined database. The information is not used in the present version of the regional model, but will be needed when the new derailment model will replace the present one.

We can also use information about straight or curve tracks. From one of the track registers, the existence ratios of curve are calculated along the line. We assume that the existence affects the divergence of post-derailment scenarios.

As one example, combined track conditions of a short part in Tohoku line are shown in Table 3-1.

Table 3-1: Examle of Track Conditions

From 354.26 km to 357.38 km from Tokyo Station (During Sendai Station and Frukawa Station)

Structure Type	START [km]	END [km]	Curve Ratio	Length [m]	Embankment Type
Bridge	354.26	354.31	0	46	
Viaduct	354.31	354.63	0	319	
Embankment	354.63	354.66	0	30	Cut-off wall
Tunnel	354.66	355.14	0.48	485	
Embankment	355.14	355.18	1.00	35	Cut-off wall
Viaduct	355.18	355.22	1.00	40	
Embankment	355.22	355.27	1.00	49	Cut-off wall
Viaduct	355.27	355.27	1.00	1	
Tunnel	355.27	355.71	1.00	440	
Viaduct	355.71	355.83	0.18	125	
Embankment	355.83	356.08	0	250	Cut-off wall
Tunnel	356.08	356.16	0	80	
Viaduct	356.16	356.25	0	87	
Tunnel	356.25	357.38	0	1133	

Probability of Different Scenarios

To identify all possible scenarios related to a derailment, one can use an event tree as shown in Figure 3-3. To calculate the probability of each scenario, the probability of each branch should first be determined. Each probability on a branch is determined as listed below;

- The probability of earthquake consists of the frequency of the earthquake that are provided in the earthquake model by RMS^{TM} as we explained in the previous section.
- The probability of SEWS is calculated by the equation 3-2 for each of trains that is on the track at the

time of the earthquake.

- To take the contribution of each track condition to all possible scenario into account, the ratio of length of each part for the traveling distance which a train runs for from S waves arrive at the train or the train starts the brakes triggered by SEWS to the train stops. (Traveling Distance for Stop)
- Probability of derailment is calculated by two approaches; derailment caused by seismic vibration and caused by damage of tracks. The details of these approaches are discussed in following section.
- The existence ratios of curve are calculated as a ratio of curve length for the length of each track structure.
- We assumed that the probability of whether a train goes to right or left is equal, namely 0.5 each.
- The existence of incoming train is calculated as the ratio of conflicted length that both trains run during the traveling distance for stop. First, the existence of incoming train within 10km is examined. Comparing the traveling distance between the objective train and the incoming train, the ratio of conflicted length is calculated. If the conflicted length corresponds to the length of a selected track part, the existence is equal to 1. If the conflicted length is shorter than the length of the selected track part, the existence is shown as a fraction.
- As we discussed in chapter 2, the probability of severe secondary accidents is about 0.28. The probability of secondary accidents adding the curve case is about 0.44.

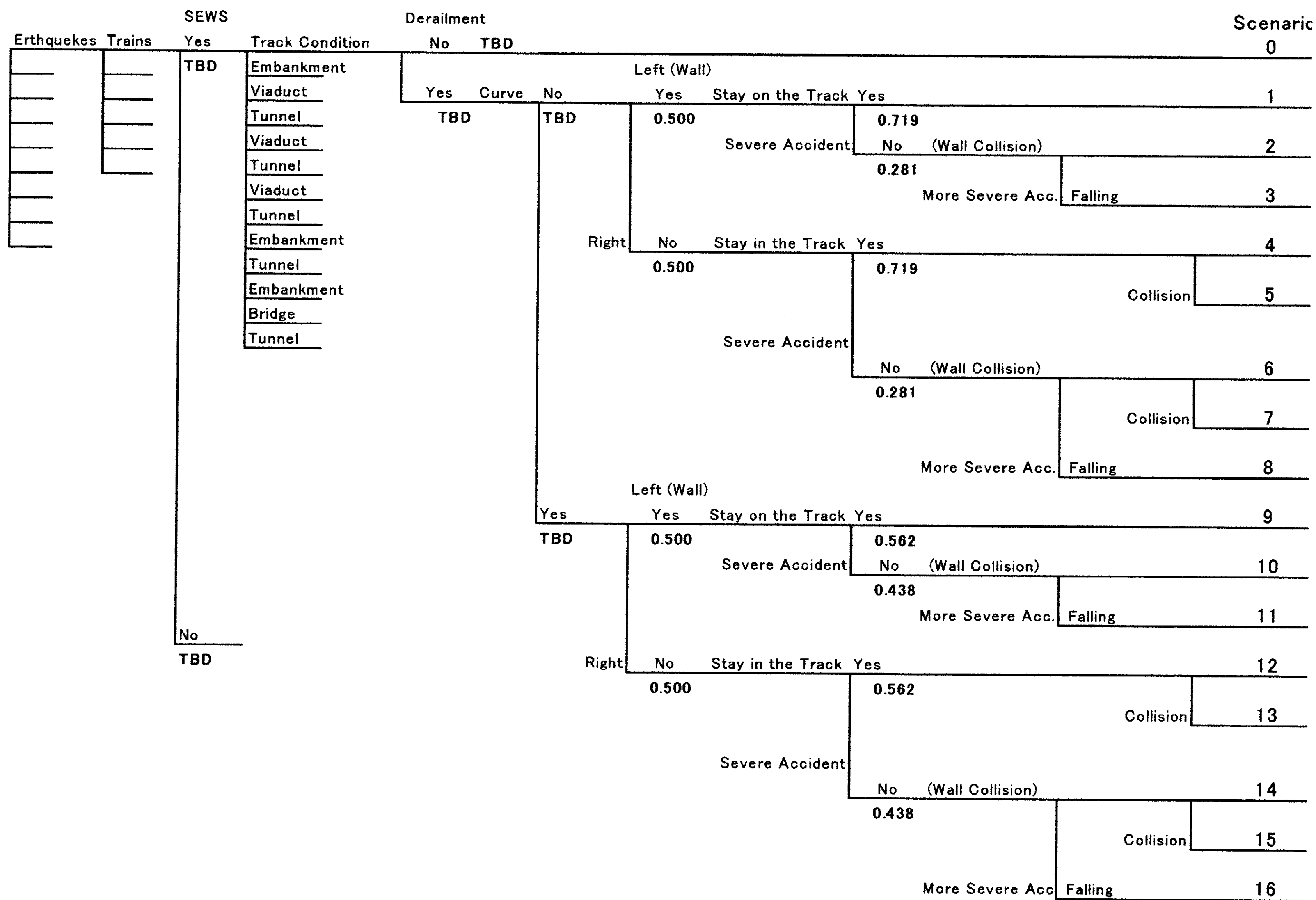


Figure 3-3: Event Tree for Derailment Scenarios

Probability of Derailment

As in the JR East system, the probability of derailment is calculated considering both derailment caused by seismic vibration and caused by damage of tracks. This is explained next.

- **Attenuation Equation**

To estimate the intensity of seismic ground motion, the JR East system uses an attenuation equation in terms of spectral intensity (*SI*). For example, the *SI* value is used in JR East to determine whether to restrict train operation after an earthquake occurs.

SI value is average of integrated velocity response spectrums (S_v) whose structural periods (T) are different from 0.1 sec to 2.5 sec and a structural damping $c = 0.2$. It is said that the *SI* value correlate closely with the structure damage caused by seismic vibration.

$$SI = \frac{1}{2.4}\int_{0.1}^{2.5} S_v(T|c = 0.2)dT \qquad \textbf{3-3}$$

The attenuation equation, by Molas. et al.(1995), is ;

$$\log SI = -1.64 + 0.62M - 1.3\times10^{6}r - \log r + 2.3\times10^{6}h + 0.18 + \varepsilon \qquad \textbf{3-4}$$

where M is magnitude, r is the distance from the epicenter [km], and h is the depth of the hypocenter [km]. ε is a manually distributed term with mean value zero and standard deviation 0.26.

- **The Probability of Derailment Caused by Seismic Vibration**

In order to evaluate the probability of derailment due to seismic vibration, former research (Shimamura et al. 2006) used a numerical simulation model of a train. Derailment was assumed to occur if the wheel moves more than 70mm relative to the rails. 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 may be set to 0.05. Eleven recorded earthquake motions were scaled to produce 19 set values of *SI* (*SI* = 10, 15, 20...... 100 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 3-4

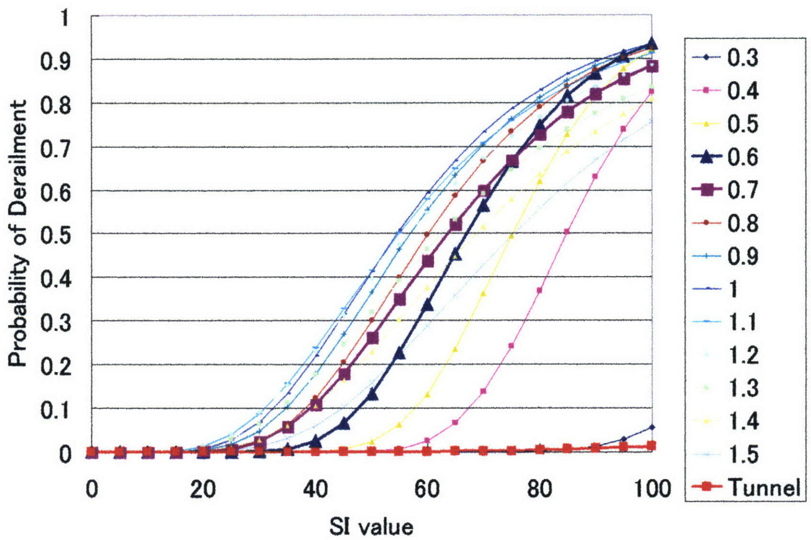


Figure 3-4: The probability of Derailment Caused by Seismic Vibration as a function of *SI* value, for different natural periods of the supporting viaduct

– The Probability of Derailment Caused by Damage of Facilities

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 by JR East using same scaled historic ground motions as mentioned above (Shimamura et al., 2006). Six types of viaducts were selected as numerical viaduct models, and four damage levels were considered. The definition of the damage 1 is the limit of yielding of shearing and repair is not needed, the damage level 2 is the damage that requires repair on case-by-case basis, and that of the damage level 3 is the damage that requires repair. The damage 4 is absolute deformation level. The calculated fragility curves of viaducts in terms of SI are shown in Figure 3-6.

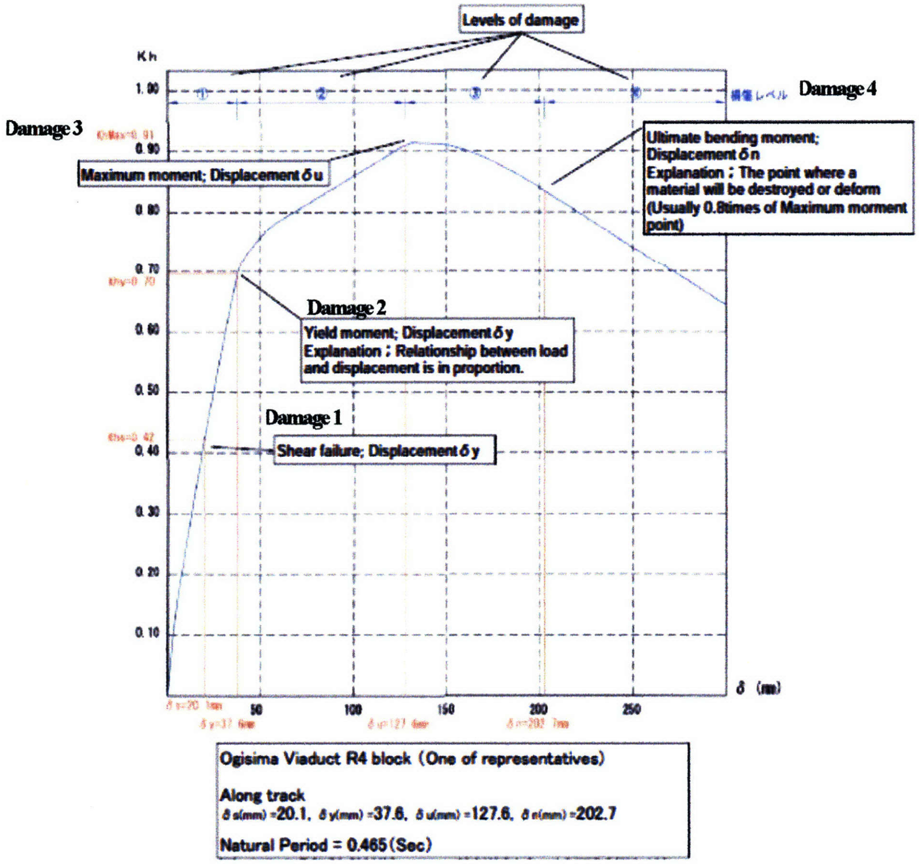


Figure 3-5: Definition of Damage Levels

From Figure 3-6, one can see the significant difference between the Damage 2 and the Damage 3. Although the definitions of the damage levels are made based of physical characteristics, the relationship between derailment and these physical phenomena was not examined before. Because of this significant difference, the probabilities of facility damage that are calculated by each damage level are also different critically. We examine the issue later in the comparison of the simulation results.

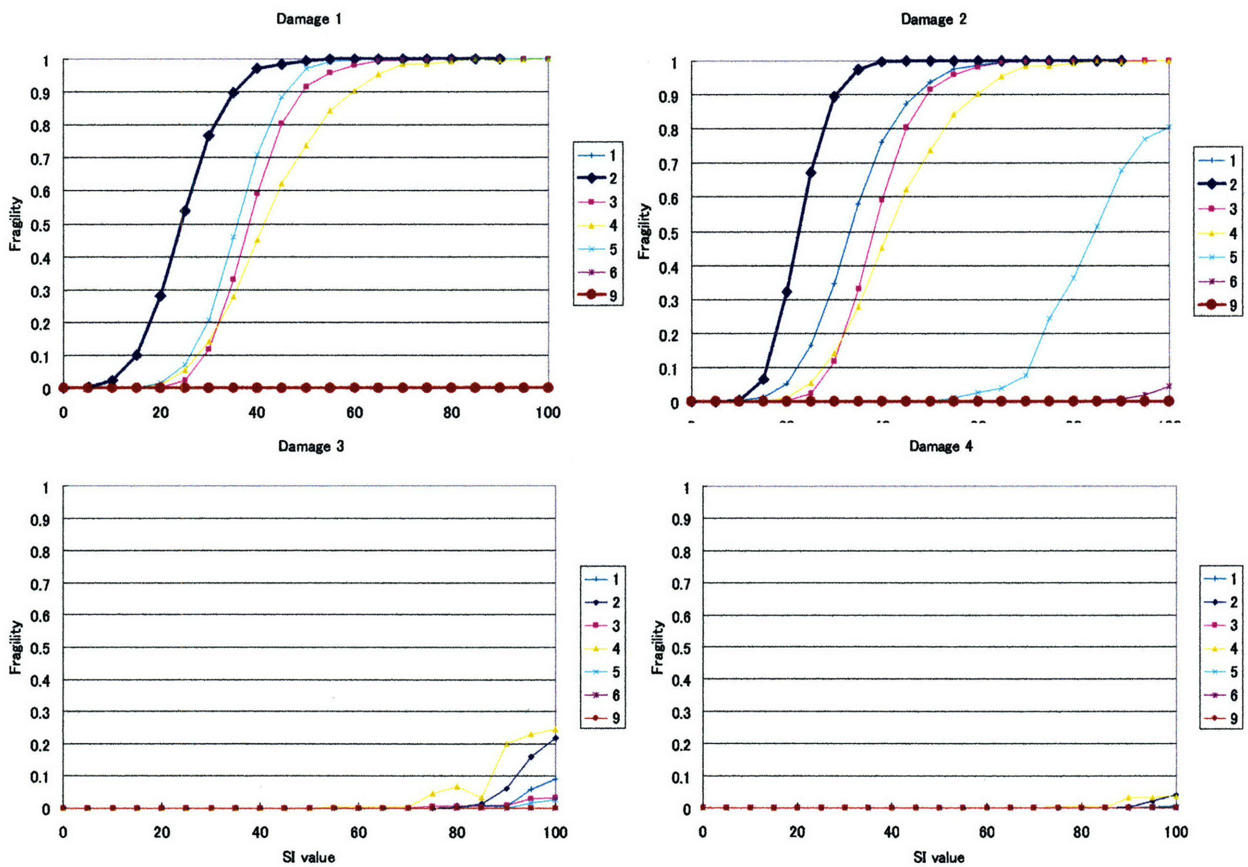


Figure 3-6: The Fragility Curves for Four Damage Levels

In the current JR East system, a viaduct can be selected as only one type of structure, but in the new system, the several track conditions, not only viaduct but also bridge, embankment, and tunnel, can be selected. The fragility curves should be selected for different track conditions appropriately, and the different probabilities due to damage can be calculated.

Papadimitriou et al. (1995) considered the fact that damage varies from location to location along the track. Papadimitriou accounted for spatial dependence by using a model with clustering of the damaged/non-damaged viaduct spans. This is also the model considered here.

$$P_{d\_damage} = 1 - e^{(N_{span} P_{damage})} \qquad \textbf{3-5}$$

where P_{d_damage} is the probability of derailment caused by facility damage, N_{span} is the number of spans, and P_{damage} is the probability of damage. In our system, P_{damage} is calculated for each of track parts and N_{span} is change dependant on the length of these parts, while P_{damage} and N_{span} are considered for continuous one viaduct in the JR East system.

Monte Carlo Method

Monte Carlo method is a stochastic simulation technich to determine one phenomenon from large number of phenomena. After all probabilities for all possible scenarios are calculated as explained above, we apply the Monte Carlo method for the selection of events to simplify calculations.

A random number, which is from 0 to 1, is generated, and an event whose probability that calculated above corresponds to the random variable is selected.

Consequences

The consequences which was discussed in the chapter 2 can apply to every possible scenario in the event tree, if the train speed and other conditions are obtained. For example, if a train overturns after derailment caused by an earthquake, it runs at 275 km/h, it can remain on the track, and fortunately there is no oncoming train, the scenario 6, the rate of miner injuries is 0.252, that of serious injuries is 0.377, and fatality rates is 0.095.

In reality, the consequences flexible dependant on different situations, such as date/time, the number of passengers, operational delay, etc. In terms of the number of passenger and date/time, we will explain a model later. Using the date/time-passenger model, we can decide the number of casualties and fatalities. For example, if the earthquake occurs on weekday at 8am between Sendai and Furukawa, the injuries and fatalities can be estimated as follows.

The average total number of passenger = 618.9

The change rate = 1.188

$$Minor = 618.9 \times 1.188 \times 0.252 = 185$$
$$Serious = 618.9 \times 1.188 \times 0.377 = 277$$
$$Fatal = 618.9 \times 1.188 \times 0.095 = 70$$

Calculating the consequences for all selected scenarios, the risk of whole network can be estimated. However, these consequences that we calculated in this research are expected consequences. In order to simulate the derailment risk more precisely, uncertainties of the consequences should be considered. This will be conducted in the second phase of this project.

Arrangement of data for the Tohoku Shinkansen Line

To focus on the Tohoku Shinkansen line in the examination of validity of this regional model, we arranged data such as track conditions, a timetable, and the number of passengers categorized by data and time band.

- **Track Conditions Along the Tohoku Shinkansen Line**

We arranged the track condition database along the Tohoku Shinkansen line by the way that we discussed in the previous section. In the database, 1535 structure parts are included in a inbound track, and 1576 structure parts are included in a outbound track.

- **Time Table of the Tohoku Shinkansen Line**

In order to analyze the real situations, we use the actual train timetable for the period from 2005 to 2006. The timetable covers 669 trains including seasonal and other special trains. Using this timetable and the time of the earthquake, one can determine the location and speed of trains along the line, evaluate the likelihood of head-on collision in the case of derailments etc. Trains that are in between stations are assumed to run at full speed for that segment. For example, between Tokyo and Omiya, the highest speed is 110 km/h. If the train is between Omiya and Morioka, it is 275 km/h. If the train is between Morioka to Hachinohe, it is 260 km/h. If the train is in a station, the train speed is zero. If SEWS triggers alarm, the train starts braking. The reduced speeds are calculated for each of track parts.

Date and Time Band Related to the Number of Passengers

When a train derails, the number of passengers on the train affects the severity of the consequences. The number of passengers that a train has depends on date and time of the earthquake, and the section of a railroad line. We estimated the number of passengers using the annual ticket sales for the year 2004 and timetable data. From the ticket sales data, we obtained the average of the number of passengers for each section, and we also found change rates of passengers dependent on date and time. The mean annual number of passengers for each section of the Tohoku Shinkansen line is shown in Figure 3-7.

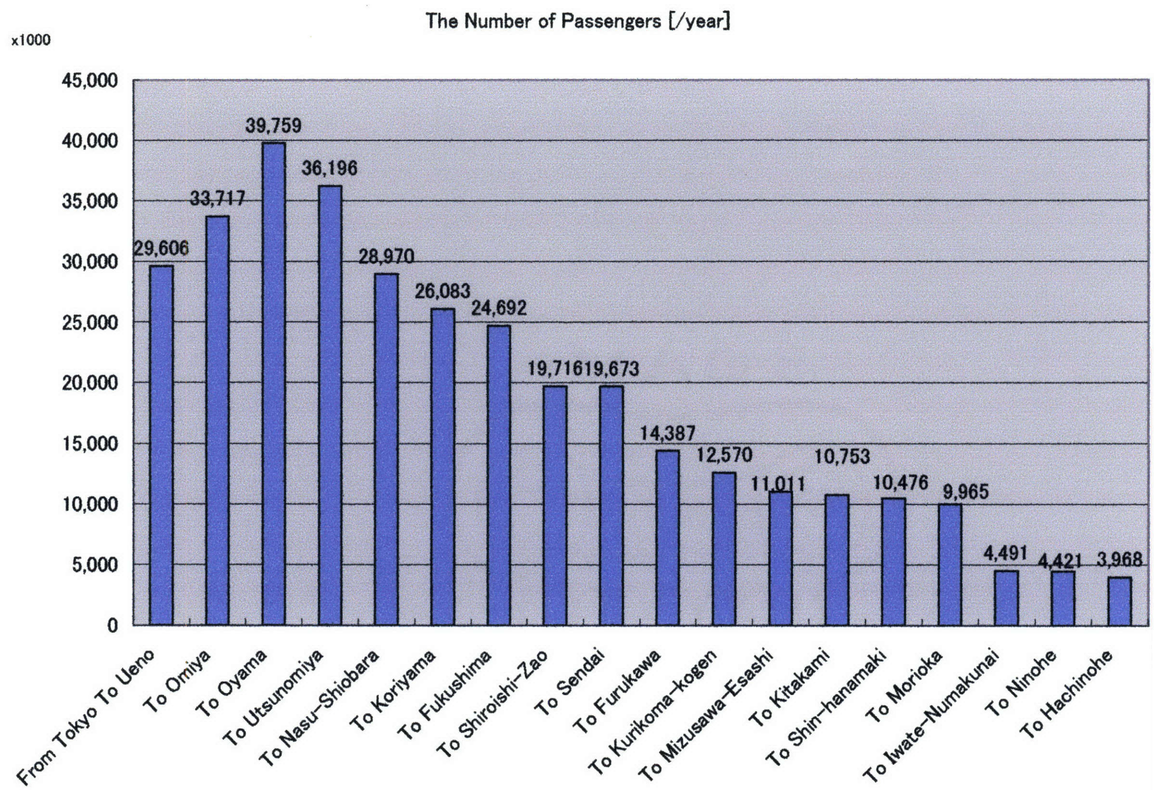


Figure 3-7: The Number of Passengers par Year

We divided these mean annual numbers by the number of trains to obtain the average number of passengers par train for each section. The number of trains for each section was observed from the timetable. We assumed that special trains and seasonal trains are used to meet the demand on holidays or vacations. From June to August 2006, in the timetable for Tokyo station, there are 74 basic trains that are operated daily and 19[3] special trains that are operated on holidays or vacations. The ratio of special to basic trains is 0.257. Although the operation dates of special trains are different, the average operation dates of them are 7.53 days. Because we counted the number of summer holiday season, it should be larger than that of non-holiday season. It should be interpreted to smaller numbers to spread them to one year. We set the rate of special trains in one year to 0.2. On average, the special trains operate 5 days in three months. The average number of passengers per train for each section is obtained as follows.

[3] We count the trains that are used more than 30 days in three months.

Table 3-2: Average Passengers Par a Train

	Total Passengers	Basic Trains	+Special Trains x1.2	Average Passengers par a Train
		345 days	20 days	
From Tokyo To Ueno	29,606,103	147	176.4	545.8
To Omiya	33,716,573	147	176.4	621.6
To Oyama	39,758,844	147	176.4	733.0
To Utsunomiya	36,195,511	146	175.2	671.9
To Nasu-Shiobara	28,970,343	147	176.4	534.1
To Koriyama	26,083,218	130	156	543.7
To Fukushima	24,692,134	118	141.6	567.1
To Shiroishi-Zao	19,716,151	116	139.2	460.6
To Sendai	19,672,963	117	140.4	455.7
To Furukawa	14,387,429	63	75.6	618.9
To Kurikoma-kogen	12,570,026	63	75.6	540.7
To Mizusawa-Esashi	11,010,915	63	75.6	473.6
To Kitakami	10,753,382	63	75.6	462.6
To Shin-hanamaki	10,476,451	63	75.6	450.7
To Morioka	9,964,520	63	75.6	428.6
To Iwate-Numakunai	4,491,197	32	38.4	380.4
To Ninohe	4,420,801	32	38.4	374.4
To Hachinohe	3,968,345	32	38.4	336.1

To consider the effects of date and time, we assumed that the number of passengers is proportional to the planned number of trains, which is shown in Figures 3-8 and 3-9 for different times of day and for ordinary trains and all trains, respectively.

This assumption may not be very accurate, especially some particular cases such as in the early morning or long distance trains. In the early morning, a train usually runs with few passengers. A longer distance train should run during some sections in that customers might not have any demands. However, JR East operators usually try to do their best to meet the demands and to avoid wastes of services when they plan the timetables. It can be expected that there are a certain degree of correlations between the actual number of passengers and the timetable.

The average number of ordinary trains simultaneously in operation is 25.6. One can see in Figure 3-8 that there are two peak time bands, one in the morning and the other in the evening. This reflects the pattern of commuting or business trips on weekdays. Figure 3-9 shows the total number of trains including special and seasonal trains. The average number is 39. This figure includes all trains regardless of operating date. Sometimes the trains operate on slightly flexible schedules, especially concerning special trains, but that has all been taken into account. In this case, there is no striking peak time band. The shape of the function is similar to a trapezoid. This means that the demand in different time bands average out on weekends and holidays. Based on these observations, we decided to use the time bands shown in Tables 3-3 and 3-4. We also decided the change in rate from the average rider ship on the time band. The average number of passengers riding on a train within a specific time band can be calculated by multiplying average rider ship from in these tables.

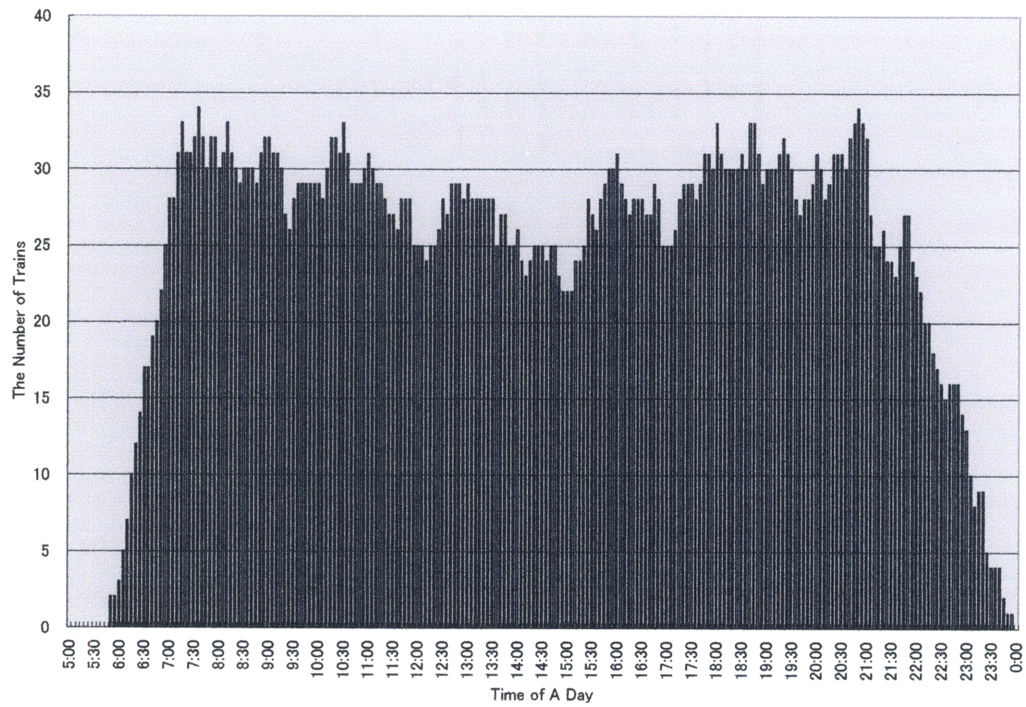


Figure 3-8: Number of Trains in the Basic Timetable

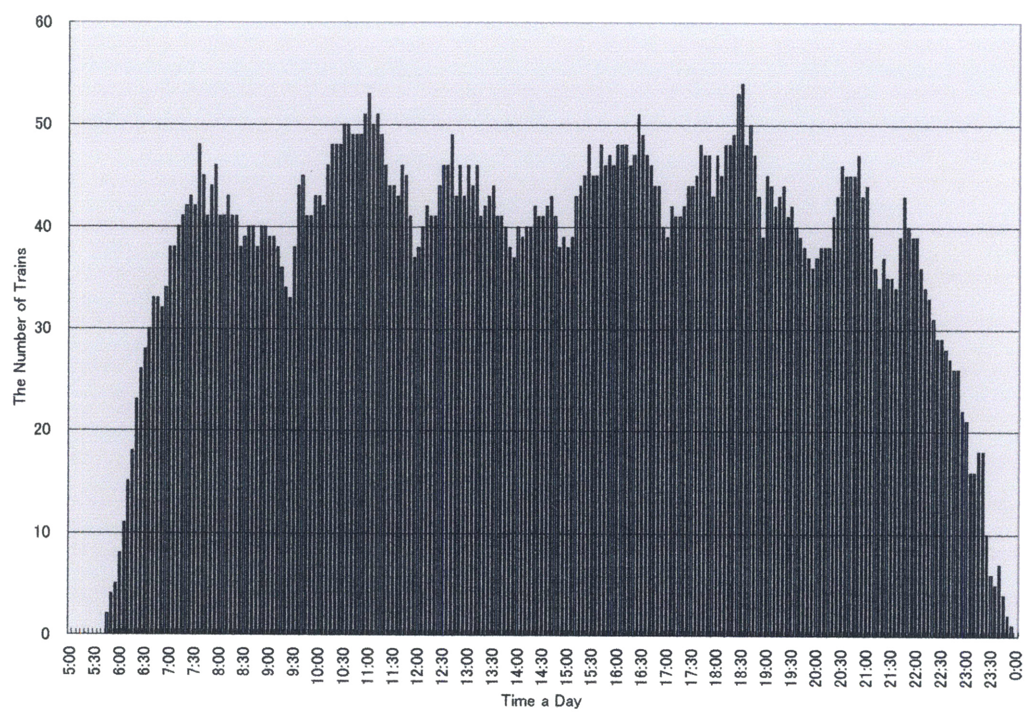


Figure 3-9: Number of Trains in the Timetable Including Special and Seasonal Trains

Table 3-3: Time Band of Weekday Operation

Time	– 7:00	7:00 – 9:00	9:00 – 17:30	17:30 – 21:00	21:00 –
Time Band	Early Bird	Morning Peak	Day Time	Evening Peak	Night Owl
Rate against average	0.529	1.188	1.052	1.190	0.625

Table 3-4: Time Band of Weekends and Holiday Operation

Time	– 7:00	7:00 – 21:00	21:00 –
Time Band	Early Bird	Day Time	Night Owl
Rate against average	0.547	1.115	0.658

3.2 Comparison with the JR East System

The current JR East system and the system proposed here use the same way to calculate the probability of derailment due to track motion and the probability of facility damage, but results are somewhat different. In the current system, the risk is analyzed segment by segment that corresponds to electrical section along the line (Electrical segment). The probability that a train is in the segment is considered for a random point in time during the day. By contrast, the new system considers the train timetable and several other databases such as land registers. Hence the proposed system can analyze the risk more precisely and realistically. The actual location of different trains at the time of the earthquake can be considered as well as the train speed. From this information, the proposed system can calculate whether and when the SEWS triggers an alarm, when the train is subjected to the strong S wave phase that can be estimated the earthquake magnitude and epicentral distance (Boatwright et al., 1986), and the distance traveled by the train following the alarm. The existence of oncoming trains can be also investigated in detail. For the facilities on which the train runs and for times from S wave arrival to the train stop, the probabilities of damage are assessed. Considering the spatial dependence of damage along the track (Papadimitrio, 1995), one can obtain the probability of derailment caused by the facility damage. The current JR East system considers spatial dependence of the damage conditions based on the assumption that the train runs on a viaduct. In the new system, we consider spatial dependence in each segment that corresponds to a unit of each track condition encountered by the train (segment of track condition), and the probability of derailment should be calculated more accurately. The differences between the current JR East system and the new system are shown in Table 3-5.

Table 3-5: The difference between JR East System and New System

	JR East System	New System
Set the time of earthquake	Not available	Available
Track Support Structure	Viaduct	Use real land registers. The Tohoku line is divided into over 1500 segments. Within each segment, the track support structure is classified into 4 types; viaduct, bridge, embankment, and tunnel.
Objective of Calculation	Selected segments that correspond to electrical sections of a line and are 30 to 50 km long.	Entire network
Place of Train	A segment in which a train runs.	According to actual timetable
Coming train	Not considered.	Considered.
Representative distance from epicenter	Calculated using the start point of the segment	Calculated using the location where the S wave arrive at the train or the place where the train can stop if the SEWS works well.
The distance that a train runs if SEWS does not works	Distance set to 1000 km.	Assume that the train stops at the next station if the train runs between two stations
Prob. of derailment by seismic vibration	Applying the distribution of the train-rail displacement obtained by a dynamic train simulation model to the estimated viaduct motion, the probability of exceeding 70mm of relative displacement is calculated.	Same as JR East System
Calculation of prob. of damage	Calculated fragility curves of viaducts in terms of SI are applied to the estimated viaduct motion.	Same as JR East System
Prob. of derailment due to facility damage	The dependence of damage is considered based on the assumption that the train runs on a viaduct	The dependence of damage is considered for each structural support that exists
Scenarios	Derailment due to vibration and damage, and risk of delay of trains	16 scenarios including head-on collision with an oncoming train.

To assess the effects of these differences, we have compared the derailment risk using these two systems for 14 selected earthquakes (see Table 3-6). In order to evaluate the risk under similar conditions, we use the same damage fragility curves and train derailment probabilities. We also focus on one electrical segment (No. 49) in the JR East system, and a target train (7900B), which is in the segment 49 at the time of the earthquake. The conditions are shows in Table 3-7. In the JR East system, the probability of derailment due to facility damage is calculated as an inner process without the external indication of the result. Because the probability of derailment due to facility damage is calculated differently by the JR East and the new system (See Table 3-5), the results are different. In order to compare the probability of damage calculated by those two system, we translate the results of the probabilities of derailment due to facility damage in JR East system to the probabilities of facility damage. The comparison results are shown in Table 3-8.

Table 3-6: The Sample Earthquakes

Serial No	Name	Magnitude	Frequency	Distance from Epicenter to Segment 49
15668	Tohoku Inland 64	6	7.10E-05	12.42
15728	Tohoku Inland 64	5	3.92E-04	12.42
19423	Tohoku Outland 16	7	4.97E-04	30.57
19996	Tohoku Outland 20	6	1.66E-04	30.57
20066	Tohoku Outland 20	5	1.74E-03	42.18
21517	Tohoku Outland 32	7	4.95E-04	51.11
22617	Tohoku Outland 40	6	1.76E-04	47.81
22677	Tohoku Outland 40	5	1.85E-03	71.46
22742	Tohoku Outland 41	6	1.81E-04	71.46
22803	Tohoku Outland 41	5	1.90E-03	68.93
22867	Tohoku Outland 42	6	1.86E-04	100.27
22927	Tohoku Outland 42	5	1.96E-03	110.29
22960	Tohoku Outland 43	7	5.22E-04	110.29
42513	The Japan Trench (Miyagi offshore)	8.4	2.07E-05	129.26

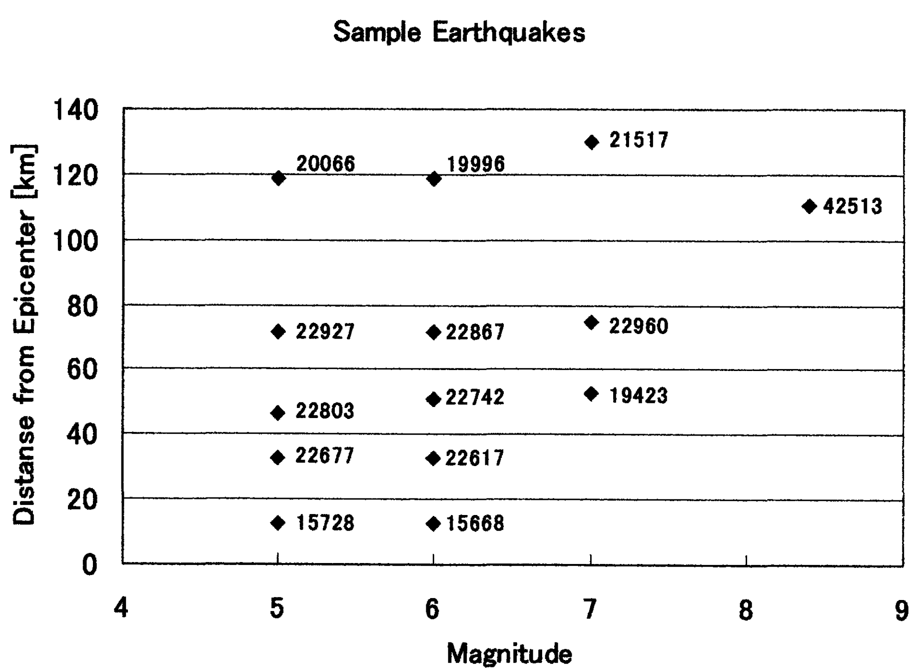


Figure 3-10: Magnitude and Epicentral Distance of Sample Earthquakes

Table 3-7: Condition of Calculation

	JR East System	The New System
Time of the earthquake	Not applicable	11:01 am
Focus of calculation	Segment 49 From 286.2 to 303.3 km from Tokyo Between Shiroisi-Zao station and Shin-Tsukinoki SST	Train 7900B Leave Sendai at 10:50am for Tokyo at 12:40am At 11:00am, 7900B is in Segment 49
Track conditions	Viaduct Horizontal natural period of viaduct = 0.4 [s]	Viaduct Horizontal natural period of viaduct = 0.4 [s]
	Use two fragility curves; Damage Level 2 and Damage Level 3	
Fragility for train derailment	The fragility curve of the Ogishima R14 viaduct (Natural period = 0.401)	The fragility curve of the Ogishima R14 viaduct (Natural period = 0.401)

Table 3-8: Comparison of Probabilities of damage and derailment by Vibration according to JR East System and New System

	Probability of Derailment by Vibration		Probability of Facility Damage			
			Damage Level 2		Damage Level 3	
Earthquake No.	JR East System	New System	JR East System	New System	JR East System	New System
15668	8.01E-04	1.47E-03	2.69E-02	5.38E-02	1.63E-04	2.60E-04
15728	0	1.23E-07	2.06E-05	1.17E-04	0	2.23E-08
19423	8.85E-04	6.50E-04	3.51E-02	3.24E-02	1.86E-03	1.14E-04
19996	0	9.37E-13	0	3.32E-08	0	2.64E-13
20066	0	6.26E-23	0	4.45E-14	0	2.32E-21
21517	0	3.05E-07	1.11E-04	2.16E-04	0	5.44E-08
22617	0	2.57E-06	8.86E-04	8.97E-04	1.38E-08	4.45E-07
22677	0	5.10E-12	0	1.10E-07	0	1.33E-12
22742	0	4.41E-08	3.18E-05	5.83E-05	0	8.20E-09
22803	0	5.09E-14	0	4.19E-09	0	1.66E-14
22867	0	9.78E-10	5.36E-07	4.29E-06	0	2.05E-10
22927	0	6.76E-17	0	3.84E-11	0	3.29E-17
22960	2.60E-05	5.59E-05	7.24E-03	6.76E-03	3.31E-06	9.55E-06
42513	7.35E-02	5.75E-02	4.30E-02	4.33E-01	1.39E-02	1.15E-02

In the JR East system, the results are rounded off at the eighth decimal place, and if the result is less than 1.0e-8, it is regarded as zero probability. The probability of derailment caused by seismic vibration and the probability of facility damage are obtained in the same ways in the JR East and the new system. Although the trends of the results are similar, there are some differences between the results. This is mainly because of the difference in the assumed distance between the epicenter and the train on track. In the JR East system, the representative distance is the minimum distance from the epicenter to the segment. In the new system, the distance is calculated using the actual timetable.

Next we consider the probability of derailment due to the train running on damaged tracks. The traveled distance depends on when the SEWS triggers, which determines the location and initial speed of the train before breaking. In order to compare results under same conditions, it is assumed that the train runs at the highest speed, 275 km/h, and it starts to brake at the time of S wave arrival. Under this assumption, the traveled distance after the S wave arrival is 3890 m. It is also assumed that the span is 50m, which is the value assumed in the JR East system. The number of span is 77.8. As we discussed before, the spatial dependence should be considered for precise calculation of facility damage. In equation 3-5, the dependence can be indicated as a function of the number of spans. The probabilities of derailment due to facility damage under these assumptions are shown in Table 3-9. Using the assumed earthquake frequencies, one can also evaluate the annual rate of occurrence of derailments; see Table 3-10.

Table 3-9: Probability of Derailment Due to Facility Damage
(traveled distance = 3890 m, span = 50m)

Earthquake No.	Probability of Facility Damage			
	Damage Level 2		Damage Level 3	
	JR East System	New System	JR East System	New System
15668	0.877	0.985	0.013	0.020
15728	0.002	0.009	0	1.736E-06
19423	0.935	0.919	0.135	0.009
19996	0	2.580E-06	0	2.055E-11
20066	0	3.465E-12	0	0.000E+00
21517	0.009	0.017	0	4.236E-06
22617	0.067	0.067	1.07542E-06	3.458E-05
22677	0	8.526E-06	0	1.033E-10
22742	0.002	0.005	0	6.383E-07
22803	0	3.259E-07	0	1.290E-12
22867	4.16678E-05	0.000	0	1.594E-08
22927	0	2.988E-09	0	2.554E-15
22960	0.431	0.409	0.000	0.001
42513	0.965	1.000	0.661	0.592

Table 3-10: The Annual Rate of Incidence of the Derailment Events

Earthquake No.	The Annual Rate of Incidence of The Derailment Frequency of EQ x Ptobability of derailment			
	Damage Level 2		Damage Level 3	
	JR East System	New System	JR East System	New System
15668	6.23E-05	7.00E-05	9.49E-07	1.53E-06
15728	6.30E-07	3.55E-06	0	7.29E-10
19423	4.65E-04	4.58E-04	6.75E-05	4.70E-06
19996	0	4.28E-10	0	3.56E-15
20066	0	6.03E-15	0	1.09E-25
21517	4.25E-06	8.24E-06	0	2.25E-09
22617	1.17E-05	1.19E-05	1.89E-10	6.54E-09
22677	0	1.58E-08	0	2.00E-13
22742	4.48E-07	8.20E-07	0	1.24E-10
22803	0	6.20E-10	0	2.55E-15
22867	7.76E-09	6.21E-08	0	3.15E-12
22927	0	5.84E-12	0	5.13E-18
22960	2.25E-04	2.14E-04	1.48E-07	4.17E-07
42513	2.15E-05	2.18E-05	1.52E-05	1.34E-05

The probability of derailment caused by facility damage level 2 is significantly higher than that of damage level 3 (See Table 3-9). The differences are over two digits. For example, In the case of the earthquake 15668, the probability of damage level 2 in JR East system is 0.877 and that of damage level 3 is 0.013. Same probability of damage level 2 in the new system is 0.985 and that of level 3 is 0.02. No. 42513, which has the highest magnitude among the considered earthquakes, the probability of derailment caused by facility damage at level 2 is almost 1. By comparison, most probabilities of derailment due to facility damage at level 3 are nearly 0. It can be considered to be affected by the difference of fragility curves (Figure 3-6). In Figure 3-6, the fragility curves of damage level 2 raise around 30 kine and approaches 1 around 40 kine. On the contrary, the fragility curves of damage level 2 are almost flat and never approach 1.

In the JR East research, the span length is currently set at 50m, but according to the drawings of viaducts, the actual span length is about 10m. If we use the span length 10m, the probabilities of derailment due to facility damage increase significantly. This is shown in Table 3-11.

In Table 3-11, some of the results of damage level 2 approach 1. This means that, if the earthquake occurs, derailment occurs almost surely. By contrast, the probabilities for damage level 3 are still small, except for earthquake No. 42513. Damage level 2 is damage that requires repair on case-by-case basis, whereas damage level 3 always requires repair. The relationship between the damage levels and whether derailment occurs is not distinct. The relationship should be investigated and a fragility curves that is intermediate between current level 2 and level3 should be developed.

Table 3-11: Probability of Derailment due to Facility Damage (Traveled distance = 3890 m, span = 10m)

Earthquake No.	Probability of Facility Damage			
	Damage Level 2		Damage Level 3	
	JR East System	New System	JR East System	New System
15668	1.000	1.000	0.061	0.096
15728	0.008	0.044	0	8.678E-06
19423	1.000	1.000	0.515	0.043
19996	0	1.290E-05	0	1.027E-10
20066	0	1.732E-11	0	0.000E+00
21517	0.042	0.081	0	2.118E-05
22617	0.291	0.295	5.37711E-06	1.729E-04
22677	0	4.263E-05	0	5.163E-10
22742	0.012	0.022	0	3.191E-06
22803	0	1.630E-06	0	6.449E-12
22867	0.000208322	0.002	0	7.968E-08
22927	0	1.494E-08	0	1.277E-14
22960	0.940	0.928	0.001	0.004
42513	1.000	1.000	0.996	0.989

From Tables 3-8 and 3-9 or from Table 3-11, one can see that the probability of derailment caused by seismic vibration is lower than that from facility damage. From experience and expert judgment, the probability of derailment caused by vibration should equal a exceed the probability of derailment due to facility damage. For example, the derailment of Shinkansen during the Niigata earthquake was mainly caused by critical seismic vibration. The train suffered from significant displacement caused by the different facility conditions, but the displacement did not cause permanent damage to the facility (Nakamura, 2005). The facility damage that occurred in the distance traveled by the Shinkansen was for the most part due to the derailed train. Therefore, the fragility curves of train derailment should also be revised. In a parallel study, a new derailment model is being developed, which may produce more realistic results.

3.3 Demonstration of Regional Approach for the Entire Network

Demonstration of Event Tree Analysis

If all probabilities of all branches in the event tree (Figure 3-3) are obtained, the probability of the end branches in it can be solved. As an instance, we explain the results of the probability of the all end branches for one situation that is solved for former comparison.

The conditions considered are as follows;

Earthquake Number	42513 (M=8.4)
Time of the earthquake	11:01 am
Train	7900B
Track conditions	Viaduct Horizontal natural period of viaduct = 0.4 [s]
	Damage Level 3
Fragility for train derailment	The fragility curve of the Ogishima R14 viaduct (Natural period = 0.401)

The probabilities of all events in the event tree in Figure 3-3 are calculated using all probabilities such as the probability of SEWS, the length ratio of the segment of track condition, the probability of derailment, curvature ratio, existence ratio a coming train, etc. The length ratio of the segment corresponds to the length ratio of a segment for the Traveling Distance for Stop. The existence ratio of a coming train corresponds to the ratio of the conflicted distances between a train and an oncoming train in the segment of track condition. For example, the both trains run the whole distance of a segment, the ratio is 1. If one of them stops inside a segment and the other runs whole distance of the segment, the ratio corresponds to the fraction of the traveled distance by the first car and the segment length. The probability of falling is temporarily set as 0.8 for a viaduct or a bridge. The result of a selected segment is shown in Figure 3-12. The event numbers are consistent with the number in Figure 3-6.

Table 3-12: Probabilities of Events on Branches

Events	Probabilities
SWES	0.0093
Length ratio of the segment (Viaduct 245m)	0.1000
Derailment	0.1114
Curve	0.0204
Existence ratio of incoming train	0.3080
Falling	0.8 (Temporarily set)

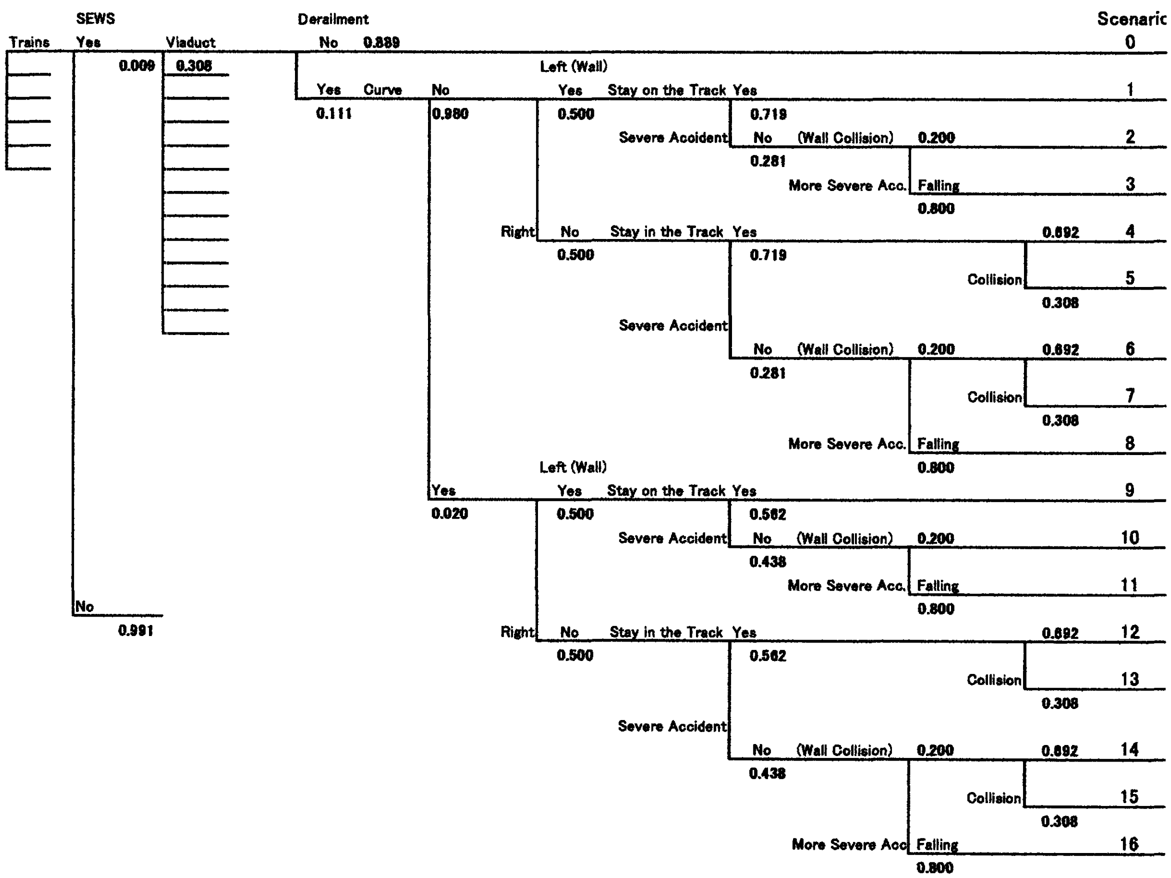
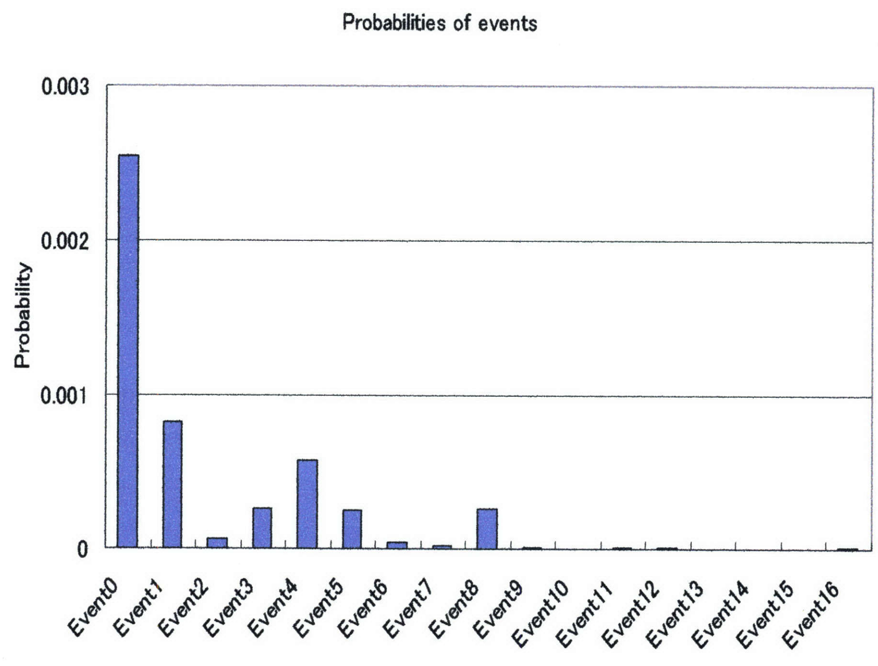


Figure 3-11: Event Tree for the Condition of Demonstration



Event0	2.54E-03
Event1	8.26E-04
Event2	6.45E-05
Event3	2.58E-04
Event4	5.71E-04
Event5	2.54E-04
Event6	4.47E-05
Event7	1.99E-05
Event8	2.58E-04
Event9	1.34E-05
Event10	2.10E-06
Event11	8.38E-06
Event12	9.30E-06
Event13	4.14E-06
Event14	1.45E-06
Event15	6.45E-07
Event16	8.38E-06

Figure 3-12: Probabilities for All Possible Events
11:01am, Earthquake No. = 42513, 7900B, Damage Level 3 (The Natural Period = 0.4)

From Figure 3-12, one can see the probability of No-Derailment (Event0) is the largest probability of them. Event1 and 4 in which there are no secondary accident such as overturning, train fall and intrusion follow the Event0. Because we set the probability of falling from a viaduct as 0.8 temporarily, the probability of Event3 and 8 are relatively high. Event5, 7, 13, and 15 include the collision with incoming train. These depend on the existence ratio of incoming train and the root probabilities of them. In this case, the existence ratio of incoming train is 0.308, and the root probability of Event5, which is the summation of Event5 and 4, is 8.25e-4. Then the probability of the Event5 is 2.54e-4. If the existence ratio of incoming train is 0, Event5 is 0 and Event4 is 1. In this event tree, the root probabilities of Event7, 13, and 15 are even small, and the probabilities of Event7, 13, and 15 themselves are also small.

From the casualty ratio and the fatality ratio also can be calculated for each event. Here we calculate these ratio on the condition that the objective train and the coming train run at 275km/h, the height of viaduct is 10 m, and show the results in Figure 3-13.

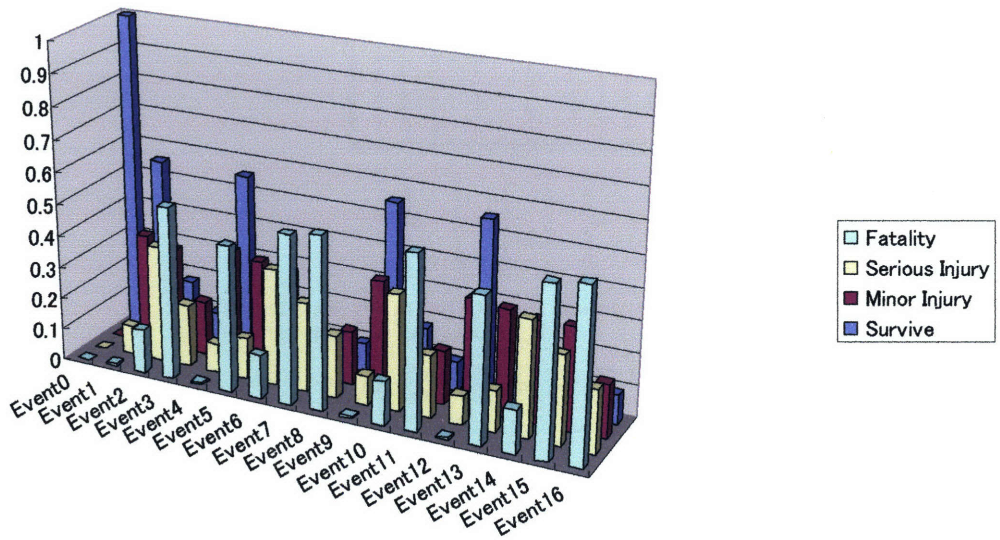


Figure 3-13: Consequences for All Possible scenario
Assumed that the train and coming train runs at 275km/h, Height of viaduct = 10m

From Figure 3-13, one can see Event0, 1, 4, 9, and 12 have no fatalities and the number of survivors is high. This means if secondary accidents such as turnover, train fall, and intrusion do not occur, the severity can be low. Event5, 7, 13, and 15 include the accident of a collision with incoming train, and the fatalities of them are large. The fatalities of falling cases, Event3, 8, 11, and 16, are also high. Therefore, the secondary accidents include the collision with incoming train and the train falling affect the severity significantly.

Considering both probabilities and consequences of events, Figures 3-12 and 3-13, the derailment risk of this example can be estimated.

Demonstration of the Regional Approach

To demonstrate the potential of the regional approach, we consider the range of consequences for the Tohoku Shinkansen line of an earthquake that occurs between 11:00 and 11:01am on a weekday. Calculations are conducted every 10 seconds during this one-minute time period. 100 possible earthquakes are selected from a earthquake model that includes 49281 (RMS^{TM}, 2003) by imposing that the magnitude is at least 6, and the epicenter is east of latitude 135° and south of longitude 43°. All trains including special trains and seasonal trains are considered. It is assumed that the Shinkansen trains have an energy management structure and elastic seats. We set the damage level for derailment to 2, although the fragility curves should probably be revised. The condition of the simulation includes the fragility curves for train derailment depend on the track system is as shown in Table 3-13.

Table 3-13: The condition of Simulation No.1 (Demonstration)

Number of Earthquakes	100	
Time / Date	From 11:00am to 11:01am / Weekday, Every 10 sec – 7 time steps	
Train Structure / Seats	Energy Management / Elastic Seats	
Damage Level	2	
Fragility Curves	Train Derailment (Natural Period [s] or Part name)	Facility Damage (Types of Viaducts)
Viaduct / Bridge	0.4	Ogisima R14 (Type 4)
Embankment	1.5	Shimo-Tokoroshima R11 (Type 5)
Tunnel	Tunnel	Ikenoshima R3 (Type 6)

In order to simplify calculations, we apply the Monte Carlo method for the selection of events. Monte Carlo method select a scenario only at once for the combination of one earthquake and one train. A random number uniformly distributed between 0 and 1, is generated, and an event whose probability corresponds to the random variable is selected.

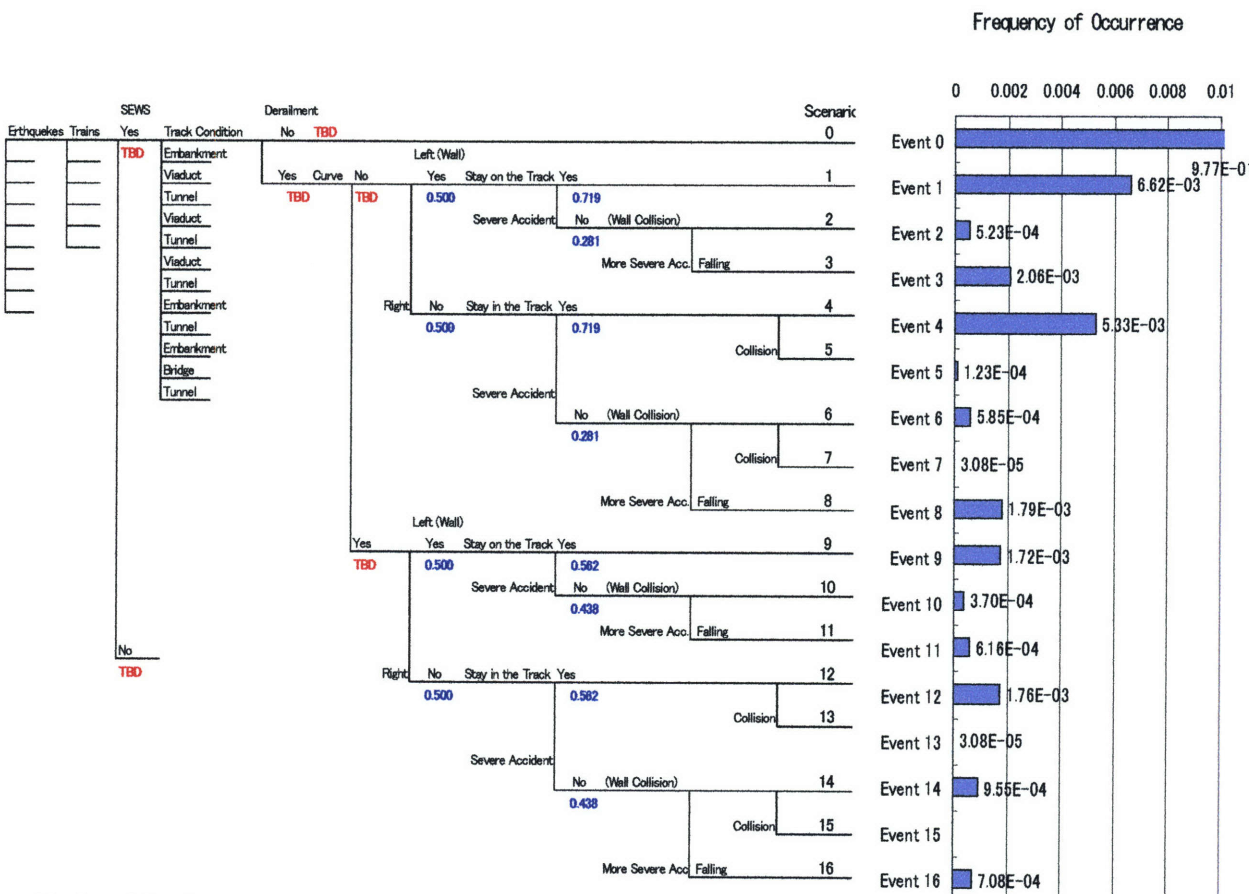
We assume that derailment and post-derailment events such as overturning, train fall, and collision occur in the same segment of track condition. In reality, derailment and post-derailment events could occur in different segments. For example, after derailment, a train might run for a while and then fall from a viaduct or collide with an incoming train. However, to simplify calculations, we assume that the segment is the same.

– **Simulation Results**

Using the conditions set in the previous section, we performed same simulations as described below. One scenario is selected for one train and for one earthquake as a result. With seismicity represented by 100 possible earthquakes, the total number of selected scenario is 32476. This is the product of the number of earthquake occurrence times (7), the average number of train on the line (46.54), and the number of earthquake magnitude and epicenteral locations (100). The simulation algorithm produced 756 derailments out of 32476 scenarios, so the empirical probability of derailment in the whole system during the 1minutes is 0.023 (=756/32476). (See Table 3-14)

Table 3-14: Results of Simulation (Conditions are indicated in Table 3-13)

The Number of Earthquakes	100
Average of Trains at the Time of EQ	46.54
Total Scenario Conditions	32476
The Number of Derailment	756



Number of Derailments

Event No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Total
Derailments	215	17	67	173	4	19	1	60	56	12	20	57	1	31	0	23	756

Figure 3-14: Frequency of Occurrence of Different Scenarios (see Table 3-13 for the calculation conditions)

From the simulation results, one can assess the frequency of various events and the expected value and distribution of casualties and fatalities, identify the type of structure and track segments that are mostly at risk, etc. This information can be used for efficient risk-reduction decision.

The frequencies of occurrence of each event that are obtained by the number of each event selected by the Monte Carlo method over the number of total scenario conditions (32476) are shown in Figure 3-14. In the results, there are six collision accidents with incoming train, which cannot be simulated in the current JR East system (Events 5, 7, 13, and 15). One can see the similarity of trends between Figures 3-12 and 3-14. The probabilities of events in which secondary accidents do not occur (Events 0, 1, 4, and 9) are relatively high. On the other hand, the probabilities of wall collision and a train fall (Events 2, 3, 6, 8 10, 11, 14 and 16) are relatively small.

Example results of the average number of derailment for each earthquake are shown in Table 3-15. (All results are shown in Appendix A) From these results, one can also analyze the annual frequency of the derailments by a following equation. (See Figure 3-15 and Table 3-16)

$$\lambda_D = \sum_{0}^{100} N_{D|EQ} \times \lambda_{EQ} \qquad \text{3-6}$$

Table 3-15: Example Results ot the Average Number of Derailment for Each Earthquake

Earthquake No.	Magnitude	Frequency	Average No. of Derailments over 7 Time Steps
124	6.8	8.23E-05	0
125	6.7	9.76E-05	0
126	6.6	1.16E-04	0
127	7.0	4.42E-04	2.57
128	6.9	1.17E-04	2.43
129	6.8	1.48E-04	2.29
130	6.7	9.37E-05	2.14
131	6.7	9.37E-05	1.43
132	6.6	1.19E-04	1.43
133	6.6	1.19E-04	2.43
134	6.5	1.50E-04	1.71
135	6.5	1.50E-04	2.86
136	7.5	1.98E-05	5.43
137	7.4	3.68E-06	5.14

From information like this, one can find which earthquakes have higher consequences and higher occurrence rates. Although the number of earthquake is limited in 100, from Figure 3-15, one can see the number of derailments that most likely to occur is 18.

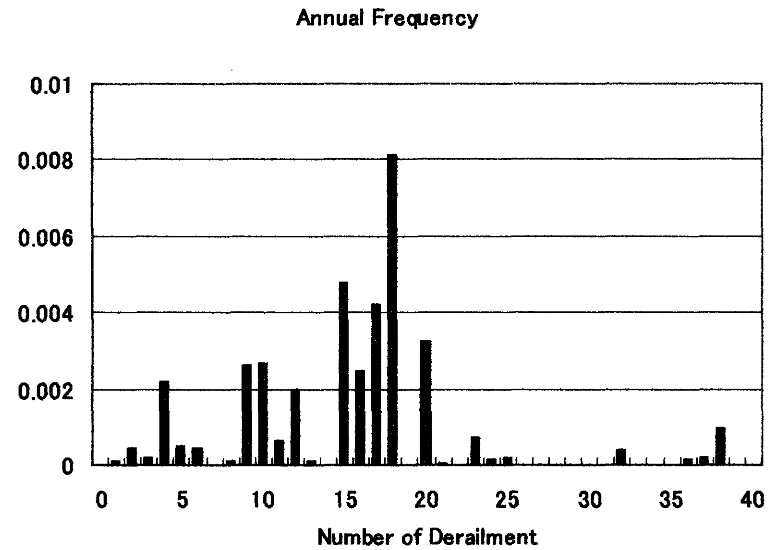


Figure 3-15: Annual Frequency of Derailment

Table 3-16: Annual Frequency of Derailment (Detail)

Number of Derailment N_D	Number of Earthquake	Annual Frequency $\Sigma N_D \times \lambda_{eq}$	Number of Derailment N_D	Number of Earthquake	Annual Frequency $\Sigma N_D \times \lambda_{eq}$
0	46	0	21	1	6.45E-05
1	1	1.09E-04	22	0	0
2	4	4.23E-04	23	1	7.27E-04
3	1	1.88E-04	24	1	1.42E-04
4	4	2.19E-03	25	1	1.75E-04
5	3	4.76E-04	26	0	0
6	2	4.25E-04	27	0	0
7	1	3.68E-06	28	0	0
8	1	9.36E-05	29	0	0
9	3	2.61E-03	30	0	0
10	4	2.64E-03	31	0	0
11	1	6.38E-04	32	2	3.73E-04
12	3	1.99E-03	33	0	0
13	1	1.08E-04	34	0	0
14	0	0	35	0	0
15	4	4.79E-03	36	1	1.32E-04
16	2	2.47E-03	37	1	1.92E-04
17	5	4.19E-03	38	2	9.86E-04
18	2	8.09E-03	39	0	0
19	0	0	40	0	0
20	2	3.23E-03			

λ_{eq} is the frequency of each earthquake

The annual expected casualties and fatalities for the line are shown in Figure 3-16. These expected values are calculated as the cumulated annual expected casualties and fatalities multiplied by the frequency of earthquake for each train. (Equation 3-7)

$$\hat{N} = \sum_{EQ=1}^{100} \lambda_{EQ} \sum_{St=1}^{7} \sum_{Tr}^{N_{train}} N_{EQ,St,Tr} \qquad 3\text{-}7$$

where $\hat{N}$ is the annual expected casualties or fatalities, λ_{EQ} is annual frequency of an earthquake, N_{EQ} is the results of the number of casualties or fatalities dependent on time steps and trains, S_t is the number of time steps, T_r is train numbers and N_{train} is the total number of trains.

From Figure 3-16, one can see the summation of annual expected casualties and fatalities is 1.29 (=0.692+0.31+0.289). The calculation was conducted under the limited condition of earthquakes. as the result of a demonstration, this means 1.29 people is likely to suffer from critical damage by derailment accidents due to earthquake per a year.

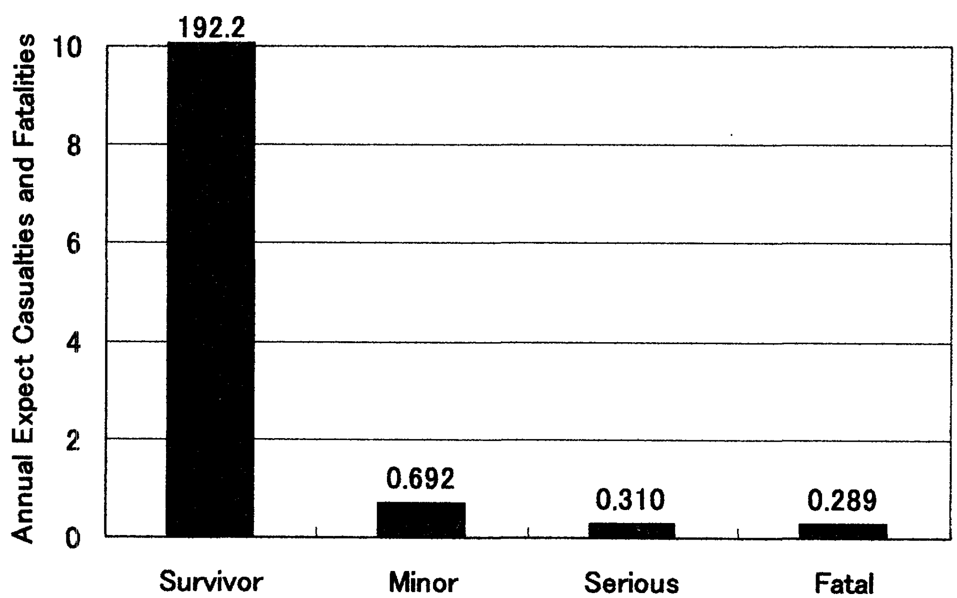


Figure 3-16: Annual Expect Casualties and Fatalities For 100 earthquakes (11:00am-11:01am)

The number of derailments and the casualties and fatalities per derailment are Figures 3-17 and 3-18 for each track type. Because most of tracks of the Shinkansen line are on viaducts, the number of derailments is largest for viaducts, but the average number of casualties and fatalities is largest for embankments. The reason is that in many cases of derailment on embankments the track are curved, and this condition induces more severe consequences in many cases.

One can also analyze the number of derailments and the number of casualties and fatalities for each section of the Tohoku line. (See Figures 3-19 and 3-20) The number of derailments is larger in northern area than in the southern area. The number of derailments from Ichinoseki to Morioka is the highest. This is because most epicenters of the selected 100 earthquakes place are in the northern area, and the epicentral distances affect the results. The number of derailments from Omiya to Utsunomiya is the smallest, but the number of casualties and fatalities per a derailment is the largest. One can guess that this is a result of the total passenger number.

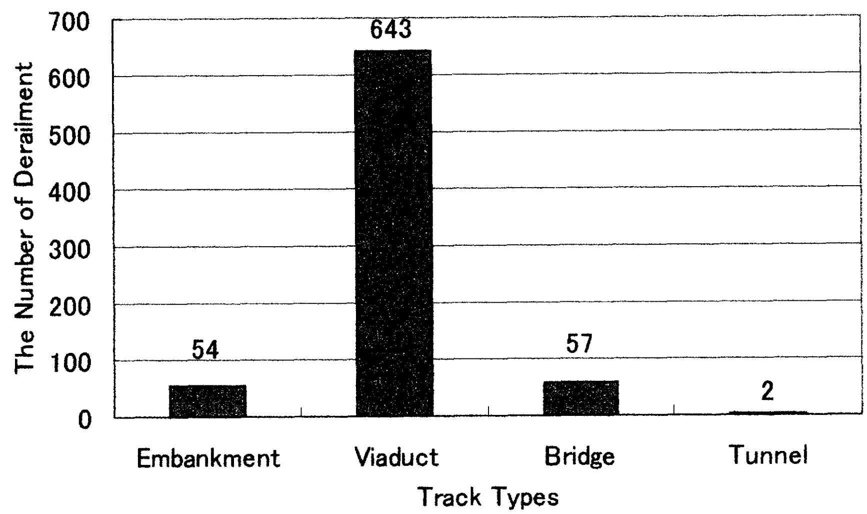


Figure 3-17: The Number of Derailment for Each of Track Types

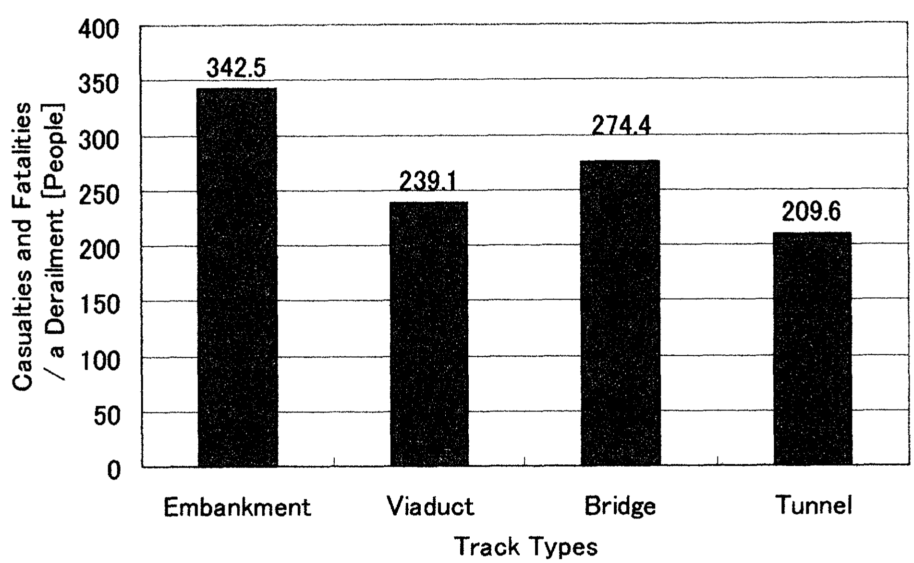


Figure 3-18: Casualties and Fatalities per a Derailment for Each of Track Types

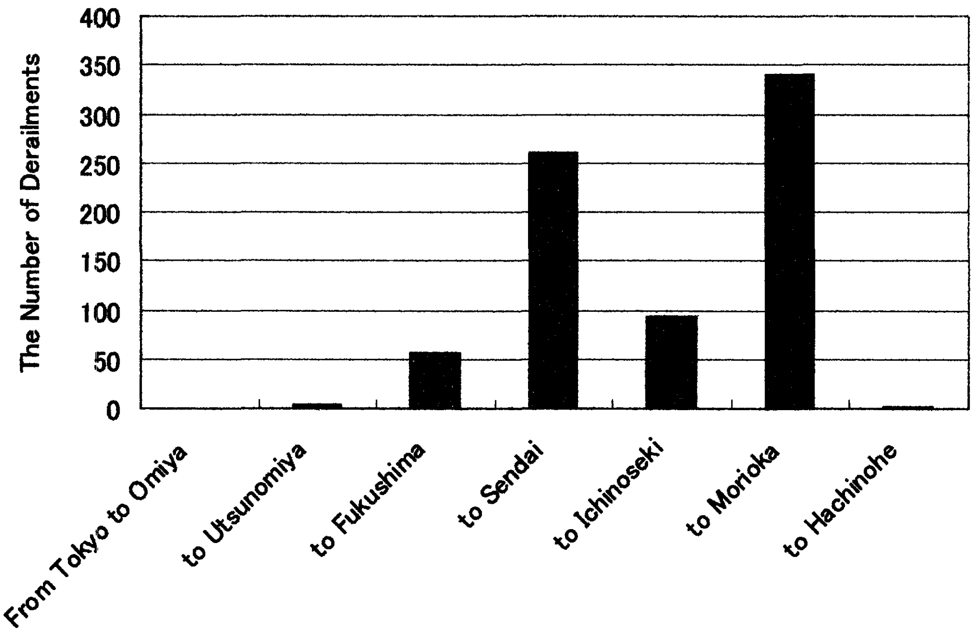


Figure 3-19: the Number of Derailment for Each of the Tohoku Line

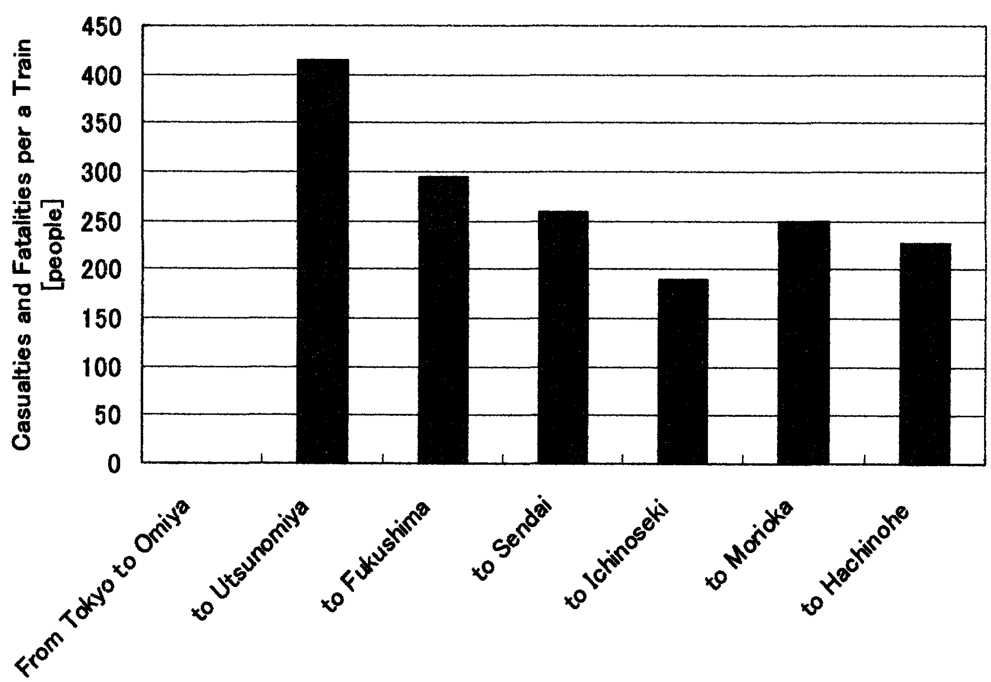


Figure 3-20: Casualties and Fatalities per a Train for Each of the Tohoku Line

Computational Issues

In this study, we have used Visual Basic for Application (VBA) in Microsoft Excel as a programming language. VBA provides an environment for programming with Excel sheets and functions. The interface is similar to that of other Microsoft software, and debugging and help functions are easy to use. Because of its user friendliness and flexibility, VBA is a powerful tool for a prototype simulation. However, VBA is not computationally efficient relative to languages such as C or Fortran. For example, running the Regional Approach simulation explained in section 3.2 took about 20 hours on a laptop computer (Pentium3; 600Mhz, 256MB RAM). To run more realistic situations, one should consider using a different programming language.

In addition, numerical efficiency may be improved by changing the structure of the current program. The current program calculates probabilities and consequences for all possible scenarios in series, without any time-saving strategy. To speed-up computations, parallel calculation methods or triggering functions should be considered.

3.4 Conclusions on the Regional Approach

We have described a new regional approach to earthquake risk and demonstrated its use on the Tohoku Shinkansen line. The main conclusions on this development are as follows.

- The new system can estimate derailment risk on the whole train network. The system uses real databases such as train timetables and registers of land and track conditions to represent conditions at the time of the earthquake more realistically than in the current JR East system. Using these data, various possible post-derailment scenarios are considered and these probabilities evaluated. The consequence model developed in § 2, is used to assess seismic risk.
- In contrast with the current JR East system, several track support conditions such as viaduct, bridge, embankment, and tunnel are considered. Hence, while the probability of derailment due to seismic vibration and the probability of facility damage are the same, the results of the two systems are different. In contrast to the JR East system, the new system can simulate multiple derailments and include head-on collisions with incoming trains. Consequences are evaluated considering the variability of the number of passengers with day, time of day, and line section.
- For illustration, we have concentrated on the Tohoku Shinkansen line and formulated a passenger number model for that line. The model gives the average ridership of the train in different segments, different days and different hours. Track condition data are also used.
- Focusing on one situation (one train, one earthquake, at a given time), we could confirm the ability of the new system to calculate the probability of end branches in the event tree including collision and train falling events. We could also confirm the ability to estimate the consequences of all events. In this way, the derailment risk in terms of the number of casualties and fatalities can be evaluated.
- We also illustrated the potential of the regional approach by applying it to the entire Shinkansen line. For this purpose, we considered 100 earthquakes occurring at 7 different times. We then analyzed several result statistics such as the rate of derailment events, the expected annual number of casualties and fatalities, etc, and how the latter vary with track type location along the line.
- From the examination of the probabilities of derailment on the Tohoku line, we have concluded that the fragility curves currently used in the JR East system should be revised. Concerning the probability of facility damage, there are significant differences between the fragility curves based on damage level 2 and these for damage level 3. Because these damage levels affect the calculation of the probability of

facility damage directly, the risk results are also very different in the two cases. Additional intermediate levels should be included. Another observation is that the calculated probability of derailment due to seismic vibration is lower than the probability of derailment due to facility damage, also when one considers damage at level 3. It is generally believed that the probability of derailment caused by vibration should be at least as large as that of derailment caused by facility damage. Therefore, we recommend that the fragility curves for train derailment and facility damage be reassessed.

Although the new system is operational, there are still some issues that remain to be considered:

- The fragility curves against derailment should be revised. This issue is being addressed in a parallel study. The model that emerges from that study should then be incorporated into the present risk analysis system.
- In this research, we assumed that a post-derailment event occurs in the same segment where derailment occurs. In reality, the post-derailment events may occur far from the derailment where the surroundings and the train speed may be different.
- To achieve the final goal of the project, the current derailment model should be replaced by the new model, and the regional approach should be extended to the whole network of JR East. To replace the derailment model, a soil database for the JR East network, which is required by the new derailment model, should be developed. To extend the regional approach to the entire JR East network, all databases such as train timetable (including train speed and deceleration information), track condition information, and seismograph information should be expanded to the entire network.
- In the developed system, we make best estimates of event probabilities and consequences. Uncertainty on risk, caused by limited knowledge of the attenuation law for seismic motion, the fragility curves for train derailment and facility damage, the frequency of earthquakes, the train timetable, the passenger ridership, and the track conditions should be assessed.
- VBA is appropriate to use for rapid or prototype programming, but to produce the final software, other programming languages are worth considering. In addition, to speed-up calculations one should consider using parallel calculation methods or triggering functions.

4 Conclusions

In order to estimate the severity of the consequences affected by the various pre- and post-derailment events that occur in the entire network, in this study we have developed a "Consequence Model" and a "Regional Approach".

Development of Consequence Model

We have developed a consequence model for train derailment in terms of passenger casualty and fatality rates. The model consists of two sub-models. The first sub-model, Derailment on Own Track Model, is for the case when the train remains in its own track. The consequences of these events are estimated from actual accident data. The other sub-model, Head-on Collision and Train Fall Model, was developed using available numerical simulation results conducted by U.S.DOT and SRI International.

– **Derailment on Own Track Model**

To quantify the consequences of derailment, we introduced a linear logistic model and used least squares or weighted least squares to fit the model to derailment consequence data. To identify the simplest suitable model structure, we used stepwise regression and statistical hypothesis testing. The final model gives the casualty and fatality rates as a function of train speed for different post-derailment scenarios.

– **Head-on Collision and Train Fall Model**

For head-on collision, we considered first the losses from reduction of occupant space. Then we consider the lost that the survivors suffer from secondary impacts with the interiors of the train. The sub-models of the occupant volume loss and the secondary impact on passenger body could be developed using the results of the available numerical simulations.

Comparing with the results of the Derailment on Own Track Model, we found the casualty rates in the head-on collision model are relatively small. That is because only fatality rates are considered in the former sub-model (the reduced occupant volume), and then casualty rates are considered only for the survivor in the latter sub-model (the secondary impact on passenger body). In addition, the models are applied not for entire train first. In contrast with the Derailment on Own Track Model in which the consequences are considered for an entire train unit, the consequences of each car in the head-on collision model are cumulated as a train after the application of the sub-models to each car.

For the train fall case, we assumed that first the train collides into a wall and then some of the cars fall if the track type is viaduct or bridge. We also assumed that cars fall freely, and collide with obstacles. Also the train fall model was developed from simulation results.

Comparing the results between the Derailment on Own Track Model and the Head-on Collision and Train Fall Model, some casualty rates of the Head-on Collision and Train Fall Model are smaller than that of the Derailment on Own Track Model. That is because only fatality rates are considered in the reduced occupant space model, and then casualty rates are considered only for the survivor in the secondary impact on passenger body model. In the Derailment on Own Track Model, the consequences are considered not for each car but for a total train. In the Head-on Collision and Train Fall Model, however, the consequences for each car are considered first, and then these are cumulated as a whole train. The difference is one of the causes of the smaller casualties in the Head-on Collision and Train Fall Model.

Regional Approach

We have developed a Regional Approach to derailment risk for the whole train network. On the network, several accidents may occur simultaneously including head-on collision with incoming train. In the system, the probability of possible derailment scenarios including head-on collisions are evaluated. From the possible scenarios, one scenario is selected by Monte Carlo method based on the calculated probabilities. Applying the consequence model developed in the first half of this thesis, the derailment risk is calculated. Using the Tohoku Shinkansen line, we showed here the regional approach can produce more realistic loss scenarios than the current JR East system can. In addition, the regional approach can produce often interesting statistics as the number of derailments for each earthquake dependent on the severalty levels of accidents, the expected casualties and fatalities for different segments along the line, etc.

From consideration of the probabilities of derailment, we recommend to revise the fragility curves that are currently in use in the JR East system, because there is excessive difference between the fragility curve of damage levels 2 and 3.

We could confirm the availability of the new system to estimate the derailment risk for entire network. As a next step, the system should be improved in the second phase of the project as follows;

- In the new system, consequences can be estimated, but uncertainty of the estimates is not considered. It would be useful to obtain the distribution or at least the variance of the risk.
- The regional approach should be expanded to the entire JR East network.
- In a parallel effort, the new derailment probability model has being developed considering the effects of soil and infrastructure conditions, and the spatial variation of ground motion and structural response. Use of the new derailment model should resolve the fragility curve issue above.
- Other languages might be advantageous from a computational viewpoint.

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6 Appendix

Appendix A: The number of Derailment for Each Earthquakes.

	EQ No.	Magnutude	Frequency	No. of Derailment	Frequency × No. Derailment
1	50	6.8	2.98E-05	0	0
2	51	6.7	3.54E-05	0	0
3	52	7.1	1.89E-04	0	0
4	53	7.0	3.52E-05	0	0
5	54	6.9	4.18E-05	0	0
6	55	6.8	4.96E-05	0	0
7	56	6.7	5.89E-05	0	0
8	57	6.6	6.98E-05	0	0
9	58	7.4	5.49E-04	0	0
10	59	7.3	1.02E-04	0	0
11	60	7.2	1.21E-04	0	0
12	61	7.1	1.44E-04	0	0
13	62	7.0	1.71E-04	0	0
14	63	6.9	2.03E-04	0	0
15	64	6.8	1.66E-04	0	0
16	65	6.7	3.10E-05	0	0
17	66	6.6	3.68E-05	0	0
18	67	6.5	2.18E-05	0	0
19	68	6.5	2.18E-05	0	0
20	69	6.4	2.59E-05	0	0
21	70	6.4	2.59E-05	0	0
22	71	6.3	3.07E-05	0	0
23	72	6.3	3.07E-05	0	0
24	73	7.7	5.80E-05	11	6.38E-04
25	74	7.6	1.54E-05	12	1.85E-04
26	75	7.5	1.94E-05	4	7.76E-05
27	76	7.4	2.46E-05	5	1.23E-04
28	77	7.3	3.11E-05	5	1.56E-04
29	78	7.2	3.94E-05	5	1.97E-04
30	79	7.4	2.00E-06	0	0
31	80	7.3	3.73E-07	2	7.46E-07
32	81	7.2	4.42E-07	0	0
33	82	7.1	5.25E-07	0	0
34	83	7.0	6.23E-07	0	0
35	84	6.9	7.39E-07	0	0
36	85	7.3	1.16E-05	20	2.32E-04
37	86	7.2	3.07E-06	21	6.45E-05
38	87	7.1	3.89E-06	17	6.61E-05
39	88	7.0	4.92E-06	17	8.36E-05
40	89	6.9	6.22E-06	16	9.95E-05
41	90	6.8	7.87E-06	18	1.42E-04
42	91	7.5	3.16E-05	23	7.27E-04
43	92	7.4	5.90E-06	24	1.42E-04
44	93	7.3	7.00E-06	25	1.75E-04
45	94	7.2	8.30E-06	13	1.08E-04
46	95	7.1	9.85E-06	10	9.85E-05
47	96	7.0	1.17E-05	8	9.36E-05
48	97	7.5	2.00E-06	17	3.40E-05
49	98	7.4	3.73E-07	15	5.60E-06
50	99	7.3	4.42E-07	12	5.30E-06

Appendix A:The number of Derailment for Each Earthquakes (Con't)

	EQ No.	Magnutude	Frequency	No. of Derailment	Frequency × No. Derailment
51	100	7.2	5.25E-07	7	3.68E-06
52	101	7.1	6.23E-07	9	5.61E-06
53	102	7.0	7.39E-07	6	4.43E-06
54	103	7.3	4.17E-04	4	1.67E-03
55	104	7.2	7.77E-05	0	0
56	105	7.1	9.22E-05	2	1.84E-04
57	106	7.0	1.09E-04	1	1.09E-04
58	107	6.9	1.30E-04	0	0
59	108	6.8	1.54E-04	0	0
60	109	7.2	2.39E-04	9	2.15E-03
61	110	7.1	4.46E-05	2	8.92E-05
62	111	7.0	5.29E-05	4	2.12E-04
63	112	6.9	6.28E-05	3	1.88E-04
64	113	6.8	7.45E-05	2	1.49E-04
65	114	6.7	8.84E-05	0	0
66	115	7.5	1.90E-04	15	2.85E-03
67	116	7.4	3.54E-05	15	5.31E-04
68	117	7.3	4.20E-05	10	4.20E-04
69	118	7.2	4.98E-05	9	4.48E-04
70	119	7.1	5.91E-05	4	2.36E-04
71	120	7.0	7.01E-05	6	4.21E-04
72	121	7.1	3.14E-04	0	0
73	122	7.0	5.85E-05	0	0
74	123	6.9	6.94E-05	0	0
75	124	6.8	8.23E-05	0	0
76	125	6.7	9.76E-05	0	0
77	126	6.6	1.16E-04	0	0
78	127	7.0	4.42E-04	18	7.95E-03
79	128	6.9	1.17E-04	17	1.99E-03
80	129	6.8	1.48E-04	16	2.37E-03
81	130	6.7	9.37E-05	15	1.41E-03
82	131	6.7	9.37E-05	10	9.37E-04
83	132	6.6	1.19E-04	10	1.19E-03
84	133	6.6	1.19E-04	17	2.01E-03
85	134	6.5	1.50E-04	12	1.80E-03
86	135	6.5	1.50E-04	20	3.00E-03
87	136	7.5	1.98E-05	38	7.52E-04
88	137	7.4	3.68E-06	36	1.32E-04
89	138	7.3	4.37E-06	32	1.40E-04
90	139	7.2	5.19E-06	37	1.92E-04
91	140	7.1	6.15E-06	38	2.34E-04
92	141	7.0	7.30E-06	32	2.34E-04
93	142	6.9	5.80E-04	0	0
94	143	6.8	1.08E-04	0	0
95	144	6.7	1.28E-04	0	0
96	145	6.6	1.52E-04	0	0
97	146	6.5	1.80E-04	0	0
98	147	6.4	2.14E-04	0	0
99	148	6.5	1.26E-05	0	0
100	149	6.5	1.26E-05	0	0