U.S. Department of Transportation

Federal Railroad Administration

Analysis of the Relationship between Operator Effectiveness Measures and Economic Impacts of Rail Accidents

Office of Railroad Policy and Development
Office of Safety
Washington, DC 20590

DOT/FRA/ORD-11/13

Final Report
May 2011

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	May 2011	Final Report

4. TITLE AND SUBTITLE
Analysis of the Relationship between Operator Effectiveness Measures and Economic Impacts of Rail Accidents

5. FUNDING NUMBERS

6. AUTHOR(S)
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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
[2] U.S. Department of Transportation
Federal Railroad Administration
Office of Railroad Policy and Development
1200 New Jersey Avenue, SE
Washington, DC 20590

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
DOT/FRA/ORD-11/13

11. SUPPLEMENTARY NOTES
Program Manager: Thomas G. Raslear

12a. DISTRIBUTION/AVAILABILITY STATEMENT
This document is available to the public through the FRA Web site at http://www.fra.dot.gov.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)
Data from 350 human factors (HFs)-related accident and 958 non-HFs-related U.S. rail accidents from January 1, 2003, through May 31, 2003, were analyzed for relationship between accident cost and crew performance effectiveness scores as estimated by the Sleep, Activity, Fatigue, and Task Effectiveness (SAFTE) biomathematical fatigue model. Property damage data was augmented by casualty cost using a combination of fatality costs and injury costs based on relationship between lost workdays and the Maximum Abbreviated Injury Scale. Preliminary analysis prompted grouping of accidents into groups based on crew effectiveness scores. Relative accident risk and relative economic risk were computed for each bin. Estimated relative economic risk (damage and casualty cost) of an HF was more *than quadrupled* for crew effectiveness scores at or below 70, *increased by a factor of 5* when scores were at or below 77 and *reduced by a factor of 4* when scores were above 90. Estimated relative accident risk of an HF increased by 62 percent when effectiveness was at or below 70 and reduced by approximately 30 percent when effectiveness was above 90. Average total cost of accidents decreased exponentially as effectiveness increased from below 70 to above 90; average total cost when effectiveness was at or below 70 was more than *triple* the overall average cost and *quadruple* the average cost when effectiveness was greater than 90. Results further validate the SAFTE for estimating work related fatigue risk.

14. SUBJECT TERMS
fatigue, railroad accidents, railroad accident cost, economics, fatigue modeling, effectiveness, relative risk, SAFTE, FAST

15. NUMBER OF PAGES
36

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	None

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std.239-18
298-102

METRIC/ENGLISH CONVERSION FACTORS

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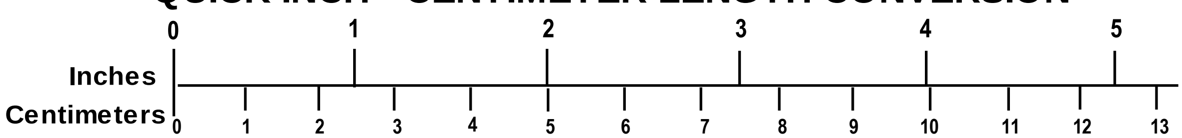

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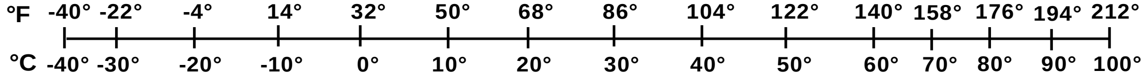

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50

SD Catalog No. C13 10286

Updated 6/17/98

Contents

Executive Summary 1
1 Introduction 3
  1.1 Purpose 3
  1.2 Background 3
  1.3 Scope 3
2 Concepts, Methods, and Sources 4
  2.1 Concepts 4
    2.1.1 Fatigue 4
    2.1.2 Fatigue Modeling and SAFTE 4
    2.1.3 Effectiveness 4
    2.1.4 Computation of Relative Risk 4
  2.2 Methods 5
    2.2.1 Crew Effectiveness Scores 6
    2.2.2 Sleep Estimates 6
  2.3 Data 6
    2.3.1 Recapitulation of Previous Study Results 7
3 Analysis of Economic Effects 8
  3.1 Measures 8
  3.2 Grouping of Accidents by Effectiveness Score Intervals 8
  3.3 Evaluation of Accident Frequency and Damage Cost by Effectiveness Scores 10
  3.4 Casualty Costs 12
  3.5 Relative Risk of Accidents and Cost 14
  3.6 Total Accident Cost Relative to Effectiveness Scores 16
    3.6.1 Accident Cost with Effectiveness Less than 70 17
    3.6.2 Statistical Test of Accident Cost Relative to Effectiveness of 70 or Below 18
    3.6.3 Relative Risk and Relative Economic Risk for Effectiveness of 70 or Below 19
4 Conclusions 21
5 References 22
Appendix A. Estimating the Cost of Casualties in Accidents Reported to the Federal Railroad Administration 23
Abbreviations and Acronyms 29

Illustrations

Figure 1. Difference in Mean Accident Cost between HFs-Related Accidents at or below a Given Crew Effectiveness Score and Those above the Same Score with Cubic Polynomial Fit ... 9

Figure 2. Total Cost of HFs-Related Accidents in Three Disjoint Crew Effectiveness Score Intervals by Accident Type ... 10

Figure 3. Number of Accidents in Three Disjoint Crew Effectiveness Score Intervals ... 11

Figure 4. Average Accident Damage Cost in Three Disjoint Crew Effectiveness Score Intervals by Accident Cause Classification ... 12

Figure 5. Total Accident Cost ($) from Casualties (dark blue) and Property Damage (light blue) Associated with HFs-Related Accidents as a Function of Average Operator Effectiveness ... 13

Figure 6. Average Total Accident Cost ($) from Casualties (dark blue) and Property Damage (light blue) Associated with HFs-Related Accidents as a Function of Average Operator Effectiveness ... 14

Figure 7. Relative Accident Risk (blue bars) and Relative Economic (damage and casualty cost) Risk (red bars) Associated with HFs-Related Accidents ... 15

Figure 8. Difference in Mean Accident Cost Including Casualty Cost between HFs-Related Accidents at or below a Given Crew Effectiveness Score and Those above the Same Score with Cubic Polynomial Fit (blue line) ... 16

Figure 9. Average Total Accident Cost ($) from Casualties (dark blue) and Property Damage (light blue) Associated with HFs-Related Accidents as a Function of Average Operator Effectiveness ... 17

Figure 10. Average Total Accident Cost ($) from Casualties (dark blue) and Property Damage (light blue) Associated with HF Accidents as a Function of Average Operator Effectiveness ... 18

Figure 11. Proportion of HF Accidents with Total Cost Greater than $80,000 Relative to Crew Effectiveness Scores ... 19

Figure 12. Relative Accident Risk (light gray) and Relative Economic (damage and casualty cost) Risk (dark gray) Associated with HFs ... 20

Figure 13. MAIS Level as a Function of LWDs ... 27

Tables

Table 1. Example of Injury Data from the FRA Casualty Detail Reports 23
Table 2. The MAIS of the U.S. Department of Transportation 24
Table 3. Examples and Descriptions of Injuries for MAIS Levels 24
Table 4. Nature of Injury Codes and Feasible MAIS Levels 25
Table 5. LWDs, Number of Injuries, and Mean MAIS for FRA Injury Codes 26
Table 6. Mean LWD and MAIS Level 27
Table 7. MAIS Level and LWDs 28

Executive Summary

Data from the Federal Railroad Administration's (FRA) database of railroad accidents, augmented by work schedules for the train crew involved, was analyzed to investigate the existence and strength of a hypothetical relationship between the economic impact (cost) of an accident and the estimated performance effectiveness of the train crew at the time when the accident occurred. This report shows that high levels of fatigue increase the average cost of human factor (HF) accidents by 300 percent and increase the risk of a HF accident by 65 percent. By contrast, HF accidents without fatigue cost less than the average HF accident and have 30 percent reduced accident risk.

Information for 1,308 railroad accidents involving the five Class I freight rail carriers that occurred between January 1, 2003, and May 31, 2005, was extracted from FRA databases. Of these, 350 were identified as having HF-related causes and 958 were caused by non-HFs (NHF). Data included date and time of the accident, property damage costs, number of injured, workdays lost by each injured person, and the number of fatalities. In a previous FRA study, the carriers had provided work histories for crewmembers on trains involved in these accidents. These data consisted of shift starting and ending times for 30 calendar days prior to and including the time of the accident and other information such as train movements relative to the crewmember's home terminal.

Crewmembers' work histories were used to estimate their performance effectiveness by applying the Sleep, Activity, Fatigue, and Task Effectiveness (SAFTE) fatigue model as implemented in the Fatigue Avoidance Scheduling Tool (FAST). The work histories were processed in FAST to compute "AutoSleep," an estimate of when each crewmember could reasonably be expected to be asleep between work shifts, and this was used to estimate crewmembers' effectiveness scores during each work interval. The crew effectiveness at the time of the accident was estimated as the harmonic mean of the individual members' estimated effectiveness scores at that time.

Property damage costs of accidents from the FRA accident database were augmented with the estimated cost of casualties. The cost equivalent for each fatality was set to $6 million, which is the value of a statistical life (VSL) used by U.S. Department of Transportation. A cost equivalent for each nonfatal casualty was computed by relating the number of lost workdays (LWDs) recorded in the FRA casualty detail database by a linear function to a score on the Department of Transportation's Maximum Abbreviated Injury Scale (MAIS) and thence to the corresponding fraction of the VSL. Property damage cost, fatality costs, and injury costs were summed to provide a total cost associated with each accident.

Preliminary analysis searched for crew effectiveness score values that would serve as plausible cut points for collecting accident cost data into bins. The difference in average property damage costs for HFs-related accidents above and below a given crew effectiveness score was found to have extreme points near scores of 77 and 90, suggesting the classification of accidents by effectiveness score into three bins ($x \leq 77$, $77 < x \leq 90$, and $x > 90$). When casualty costs were included, the lower extreme point shifted to near 70, prompting the grouping into three slightly different bins ($x \leq 70$, $70 < x \leq 90$, and $x > 90$).

The relative accident risk of HFs-related accidents in bins defined by these values was then computed. The computation of relative risk first involved calculating a ratio of the proportion of accidents within an effectiveness bin (incident fraction) to the proportion of crewmembers duty time spent within that effectiveness bin (exposure fraction). That ratio was then divided by the same quantity computed for accident risk outside the bin. Relative economic risk was computed in the same fashion as relative accident risk, except that each accident was multiplied by its cost to provide a relative measure of the consequences of each accident. The following results were noted:

- The estimated relative economic risk (damage and casualty cost) of an HF-related accident is more *than quadrupled* when crew effectiveness scores are at or below 70.

- The estimated relative economic risk (damage and casualty cost) of an HF-related accident is *increased by a factor of 5* when crew effectiveness scores are at or below 77 and *reduced by a factor of 4* when crew effectiveness scores are above 90.

- The estimated relative accident risk of an HF-related accident is increased by 62 percent when crew effectiveness scores are at or below 70 and reduced by approximately 30 percent when crew effectiveness scores are above 90.

- The average total accident cost (damage and casualties) when crew average effectiveness is equal to or less than 70 (highly fatigued) is approximately $1.6 million, which is more than *triple* the overall average cost of accidents. In comparison to accidents without fatigue (when effectiveness is greater than 90), the average cost when crew average effectiveness is equal to or less than 70 is *quadrupled*. The average total cost of accidents decreases exponentially as effectiveness increases from below 70 to above 90.

These results further validate the utility of biomathematical fatigue models (here the SAFTE model and the FAST software) for estimating work related fatigue risk. They also calibrate the model to indicate that a score of 70 or below is associated with an elevated relative risk in the number and severity (cost) of accidents.

1. Introduction

1.1 Purpose

The Federal Railroad Administration (FRA) continues to develop tools for managing fatigue in railroad operations. A previous report established a statistically reliable relationship between train crew performance effectiveness (inverse of fatigue) and the risk of an HFs accident (Hursh et al., 2006, 2008). The purpose of the current report was to use the data from the FRA database of railroad incidents, augmented by work schedules for the train crew involved, to investigate the relationship between the economic impact (cost) of an incident and the estimated fatigue of the train crew at the time when the incident occurred.

1.2 Background

In 2006, the FRA completed the third phase of a research program to demonstrate a method to validate and calibrate fatigue models for use in predicting and managing fatigue in railroad workers. A fatigue model offers the possibility of objectively assessing and forecasting fatigue so that employees and employers can schedule work and rest to avoid fatigue. A useful fatigue model needs to be calibrated to the demands of a particular job so that the measures from the model can be related to the risk of meaningful failures of human performance. One important part of calibration of a fatigue model for use as a fatigue management tool is an assessment of whether the tool can predict an increased risk of an HFs error or risk of having an HF-caused accident. As part of this assessment, FRA sponsored a project, in partnership with the five Class I freight rail carriers, to examine 2.5 years of data on accidents.

1.3 Scope

This report describes an extension of analyses performed for the FRA that investigated the relationship between accident cost and estimated crew impaired effectiveness from fatigue. The original effort developed estimates of train crew performance effectiveness using the Sleep, Activity, Fatigue, and Task Effectiveness (SAFTE) fatigue model implemented in the Fatigue Avoidance Scheduling Tool (FAST).[1] These estimates were then used to estimate accident risk based on crew member estimated effectiveness at the time of accidents, and to compare risk between accidents with HFs-related causes and those whose causes were not HFs-related. The work described herein extends that analysis to investigate the relationship of HFs-related accident (HF-related accidents) cost to estimated train crew effectiveness.

[1] Note that SAFTE is the quantitative model itself (i.e., the algorithm that defines how fatigue is estimated and effectiveness measures computed from the required inputs), whereas FAST is the *implementation* of the model in software. Since FAST is used for the actual computations, it is referred to as "the model" hereinafter, but the distinction should be kept in mind. The SAFTE model and the FAST software are both patented; rights to SAFTE are owned by the U.S. Army and licensed to Fatigue Science, Inc., owner of the rights to FAST and other software implementations of the SAFTE model (www.fatiguescience.com).

2. Concepts, Methods, and Sources

2.1 Concepts

2.1.1 Fatigue

Fatigue is more than simple sleepiness. It is a complex state characterized by a lack of alertness and reduced mental and physical performance, often accompanied by drowsiness. Fatigue is associated with symptoms including measurable changes in performance, lapses in attention and vigilance delayed reactions, impaired logical reasoning and decisionmaking, reduced "situational awareness," low motivation to perform "optional" activities, poor assessment of risk (or failure to appreciate the consequences of actions), and operator inefficiencies. Clearly the appearance of any of these symptoms in a railroad operations crew could potentially lead to incidents.

2.1.2 Fatigue Modeling and SAFTE

Although fatigue is one potential root cause for these symptoms, no direct measure or physiological marker for fatigue has ever been identified. However, the conditions leading to fatigue are well understood, and sufficiently quantifiable that the degree to which an individual is fatigued can be estimated by means of biomathematical models such as the SAFTE fatigue model. A fatigue model offers the possibility of objectively assessing and forecasting fatigue so that employees and employers can schedule work and rest to avoid fatigue.

2.1.3 Effectiveness

The SAFTE Model predicts *effectiveness* based on opportunities to sleep and time of day. Effectiveness is a metric that ranges from 0 to 100 and tracks speed of performance on a simple reaction time test. It is strongly related to overall cognitive speed, vigilance, and the probability of attention lapses or "micro-sleep" (Hursh et al., 2004; Van Dongen, 2004). Cognitive effectiveness can be interpreted as the inverse of fatigue.

In terms of cognitive impairment, an effectiveness value of 70 is roughly equivalent to a blood alcohol level of 0.08 percent, or having remained awake for 21 h following an 8-hour sleep period the previous night (Arnedt et al., 2001; Dawson and Reid, 1997). Major quantifiable factors that produce or exacerbate fatigue include a time of day between midnight and 6 a.m., insufficient sleep in the last 24 h, long intervals since the last major sleep period, accumulation of "sleep debt" since last full night of sleep, work intensity, and duration.

2.1.4 Computation of Relative Risk

In a previous report on fatigue modeling and accident risk (Hursh et al., 2006, 2008), the authors examined the proportion of accidents at a particular level of fatigue (effectiveness) relative to the proportion of work time at that level of fatigue. That analysis tested whether a fatigue model could predict an elevation of the chances of an accident relative to the chance exposure to a particular level of predicted fatigue.[2] Here we are interested in quantifying that risk relative to

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[2] In Hursh et al. (2006, 2008), relative risk was computed as the ratio of events (E) in the given category to exposure to that category (C). Here the definition follows the epidemiological usage, where relative risk is expressed as a

the alternative of not being in that state of fatigue, which is the standard epidemiological definition of *relative risk* (Armitage and Berry, 1994). *Relative risk* quantifies risk relative to other alternative conditions: it is the expected loss under a given set of conditions relative to the expected loss when those conditions are not present.[3] For an event *E* and a condition[4] *C*,

Relative risk of E given C= Prob (E|C)/Prob (E|not C)

where *(E|C)* denotes the event that *E* occurs when condition *C* is present, and *(E|not C)* the event that *E* occurs when condition *C* is *not* present.[5]

Relative risk can have any non-negative value. A relative risk of 1 means that the probability of *E* is the same whether or not condition C obtains; in other words, *E* is *statistically independent* of *C*. A relative risk greater than 1 means that event *E* is *more* likely to occur under condition *C* than when it is absent, and a relative risk less than 1 means that event *E* is *less* likely to occur under conditions *C* than when that condition is absent.

Suppose condition *C* occurs 20 percent of the time in the data set; then if 20 percent of all occurrences of event *E* occur when C obtains and 80 percent occur when *C* does not, the event *E* is independent of *C* [relative risk = 1 = (0.2/0.2)/(0.8/0.8)]. Suppose instead that 30 percent of all occurrences of event *E* occur when condition *C* is present; then the relative risk is computed as (0.3)/0.2/(0.7/0.8) = 0.24/0.14 ≈ 1.71, which means the relative risk of event *E* occurring is increased by 71 percent if condition *C* is present. If on the other hand only 10 percent of all occurrences of event *E* occur when condition *C* is present, the relative risk is (0.1/0.2)/(0.9/0.8) = 0.08/0.18 ≈ 0.44, so that the relative risk of event E occurring is reduced by 56 percent if condition C is present.[6]

In the current instance, it is natural to ask what relative risk is associated with an accident when crewmembers are in various states of fatigue relative to when they are in other states, specifically to what extent the relative risk might be magnified (or reduced) for a crew at a higher (or lower) state of fatigue. The following analysis examines both relative accident risk and relative economic risk resulting from an accident.

2.2 Methods

The SAFTE model as implemented in FAST estimates an individual's effectiveness in performing cognitive tasks as a function of the amount and timing of the individual's prior sleep and the time of day or "circadian rhythm" of cognitive functioning.

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ratio of risk of an event within a category to the risk for all events *excluding* that category (Armitage & Berry, p. 508).

[3] Note that the "loss" in question may be the occurrence of an event, as well as the magnitude of an adverse outcome associated with an event. In the current instance, the loss could be the occurrence of a railway accident, or the cost incurred by such an occurrence.

[4] For simplicity, the subsequent discussion assumes a single (pre)condition.

[5] This is analogous to the definition of risk in epidemiology, with the occurrence of an accident corresponding to contracting a disease and the crew effectiveness score falling into a given interval corresponding to the putative risk factor (e.g., see Armitage & Berry, pp. 508–522).

[6] In prior reports (Hursh et al., 2006, 2008), risk was defined as the proportion of events E given condition C, or 1.50 or a 50 percent increase, in this example.

2.2.1 Crew Effectiveness Scores

Effectiveness scores at the time of the incident were averaged among all on-duty crewmembers of the train involved. Because these scores are effectively rates for accomplishing a fixed set of cognitive tasks, the appropriate average is the harmonic mean.[7]

2.2.2 Sleep Estimates

This analysis was undertaken well after the incidents' times of occurrence. It was, therefore, impossible to collect accurate information on subjects' actual sleep patterns. Available data were limited to the start and end times of subjects' work shifts from the railroads' records, which were obtained for each subject for 30 calendar days prior to the incident time. This information, which captures all time spent by the subject on site during the interval, was augmented with railroad- and terminal-specific call and commute times. Call time represents the amount of advance notice a worker must be given (usually by telephone) by the railroad before the start of a work shift. Commute time is the railroad's estimate of the time required by a subject leaving the site at the end of a work shift to return to lodgings and make ready for sleep. These times are added to the times of the beginning and end of the work shifts to generate intervals during which the subject would be excluded from sleeping.

With the remaining time as time available for sleep, FAST was applied to compute "AutoSleep," an estimate of when the subject could reasonably be expected to be asleep between work shifts. This recursive estimate is based on reasonable assumptions about how crewmembers allocate off-duty time between sleep and other activities and has been validated against measures of sleep in other studies of railroad engineers. At any time of interest, whether the subject is modeled to go to sleep (or remain asleep) depends upon the time of day (which affects sleep quality) and the interval available for sleeping (FRA, 2011).

Once FAST has been run to generate AutoSleep for an individual, the tool is rerun using the estimated sleep intervals to generate average effectiveness scores averaged over half-hour intervals beginning at 00:01. An instantaneous effectiveness score at the time of the incident is also computed.

2.3 Data

Incident data were derived from the publicly available FRA database of railroad incidents. These data were augmented by information provided by the study railroads about work schedules for each train crewmember involved in incidents and used to validate and calibrate fatigue modeling (Hursh et al., 2006, 2008). Work schedule data consisted of on-duty and off-duty dates and times for each individual involved in an incident during the 30 calendar days prior to that

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[7] The rationale for this choice can be understood by analogy with actual speed: The average speed of a train that travels 30 miles at 40 miles per hour (mph) and then 40 miles at 80 mph is most easily computed by dividing the total distance traveled (30+40=70 miles) by the total amount of time taken (for the first stretch, 30 miles/40 mph = 3/4 h; for the second stretch, 40 miles/80 mph = 1/2 h; in all, 3/4 h + 1/2 h = 1 1/4 h) to obtain 70 miles/1 1/4 h = 56 mph. This is the same as $HM = \dfrac{30+40}{\frac{30}{40}+\frac{40}{80}}$.

incident. The railroads also provided call and commute times for originating and destination stations. The resultant data set was recently purged for data inconsistencies and now covers 1,308 accidents from the study railroads during the period from January 1, 2003, through May 31, 2005. At least one HFs cause code was associated with 350 of these accidents, whereas the remaining 958 had no HFs (NHFs) cause code associated with the accident. Of the 350 HF-related accidents, 63 were associated with cause codes that were most frequent when fatigue was high or effectiveness was low (less than 70; see Hursh et al., 2006, 2008), such as passing a red signal, excessive speed, violating train orders, or poor train handling.

Accident data used in the prior study were limited to the date and time of the accident along with primary and secondary cause codes. These FRA-defined codes indicate the factors that were identified as having caused the accident, such as passing a stop signal or exceeding authorized speed. The current study augments this information with economic impact data, also drawn from the FRA incident database. Data available from the database includes the dollar cost of damage to equipment and track. The dollar cost of equipment and track damage combined was used as the measure of economic impact. Later, in this report, we discuss the added cost of death and injury associated with these same accidents, based on data from the FRA database.

2.3.1 Recapitulation of Previous Study Results

The previous study was directed at investigating whether a fatigue model (specifically, SAFTE as implemented in FAST) could predict an increased risk of HFs-related accidents under certain conditions that cause fatigue. Incidents were separated into those with a primary and/or secondary HF cause code (i.e., a code indicating that HFs were involved) and those lacking such cause codes.

There was a reliable inverse linear relationship between crew effectiveness score and the risk of an HF accident ($r = -0.93$). No such relationship was found for NHF accidents. These results satisfied the criteria for model validation.

3. Analysis of Economic Effects

3.1 Measures

This study investigated the relationship between the cost of a rail incident and train crew fatigue. The measure used for cost was total accident damage as recorded in the FRA accident database (field ACCDMG). The measure representing crew fatigue was the combined effectiveness score (the harmonic mean of crew members' effectiveness scores) computed by FAST at the time of the accident, based on crew work schedules and the AutoSleep estimates of crew sleep patterns.

Initial inspection of the HFs cost data indicated that higher average HF-related accident costs tend to be found at somewhat lower crew effectiveness scores than is true for NHF-related accidents, particularly below 75. Moreover, lower average HF-related accident costs, particularly in comparison with average costs for NHF-related accidents, tend to be found at scores above 85. This suggested that reduced effectiveness results in relatively more expensive accidents but the exact form of that relationship was unclear from the raw data.

3.2 Grouping of Accidents by Effectiveness Score Intervals

One possible form of a relationship between the damage cost of a railway accident and the estimated fatigue of the crew members involved is for the accident cost data to behave differently in different ranges of effectiveness score values. For example, it is plausible to expect HFs-related accidents to be generally less costly when the crew effectiveness score is above 90, which value is typical of an individual working a 40-hour week who gets 8 h of quality sleep per night (see Hursh et al., 2006, 2008). The salient questions are whether effectiveness score intervals may be defined that collect accidents into distinct and distinguishable subsets on the basis of their cost, and how such intervals can be determined. Preliminary analysis indicated that HF-related accident costs may be behaving somewhat differently in the regions below 75, between 75 and 90, and above 90. To investigate this pattern further, the average cost of HF-related accidents associated with crew effectiveness scores at or below a given value and the average for accidents with scores above that value was computed. Figure 1 plots the differences between these averages for effectiveness scores of 65 and higher (above which value the average cost at or below is always greater than the average above). The difference increases with effectiveness score to a local maximum of nearly $180,000 at a score of about 77, then falls gradually to a local minimum just under $140,000 at a score of about 91, and begins to rise again to a maximum of $228,413 at a score of 100.

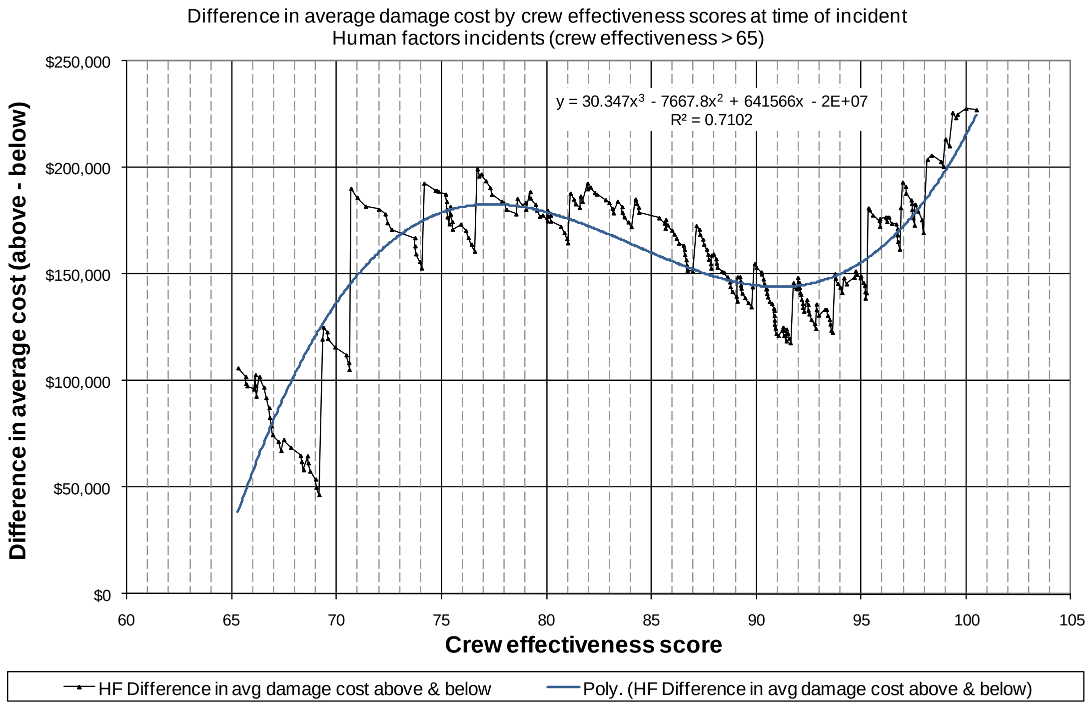

Figure 1. Difference in Mean Accident Cost between HFs-Related Accidents at or below a Given Crew Effectiveness Score and Those above the Same Score with Cubic Polynomial Fit

As the value of the effectiveness score "cut point" rises, accidents migrate from the right-hand side ("above") to the left ("at or below"). This pattern suggests that below 77 and above 91, the accidents that are being shifted to the left are costly relative to those remaining on the right, increasing the average at or below and/or decreasing the average above; between these values, the accidents shifted from right to left are relatively close to the (lower) average above that value.

The pattern of one local maximum and one local minimum is suggestive of a cubic polynomial, and in fact such a function fitted by least squares accounts for over 70 percent of the variation in accident costs in terms of the effectiveness score of the crew involved ($R^2 = 0.71$). The fitted polynomial (superimposed blue line on the accident data in Figure 1) has a local maximum at a score of 77 and a local minimum at a score of 90.

Taken together, the observations above strongly suggest that accident costs behave differently among three intervals: at or below 77, between 77 and 90, and above 90. These three intervals are used in all subsequent analyses. *Note that the value of 77 is not to be taken as a discrete threshold for judging safe from unsafe schedules; it is merely a statistical method for segregating the more expensive accidents from less expensive accidents in this sample.*

3.3 Evaluation of Accident Frequency and Damage Cost by Effectiveness Scores

The three intervals defined immediately above were used to subdivide the accident damage cost data for further investigation and define the horizontal axis in Figure 2 through Figure 5 below.

Figure 2 shows the total accident damage costs for HF-related accidents in the given intervals, breaking out from this category a subcategory labeled "Fatigue Type Cause Codes." These codes were identified in the previous report as the 10 HF-related cause codes that were more often reported when crew effectiveness scores were at or below 70. In the lowest interval, these cause codes account for over half of all costs resulting from HF-related accidents, but only one-sixth of the costs above an effectiveness score of 77.

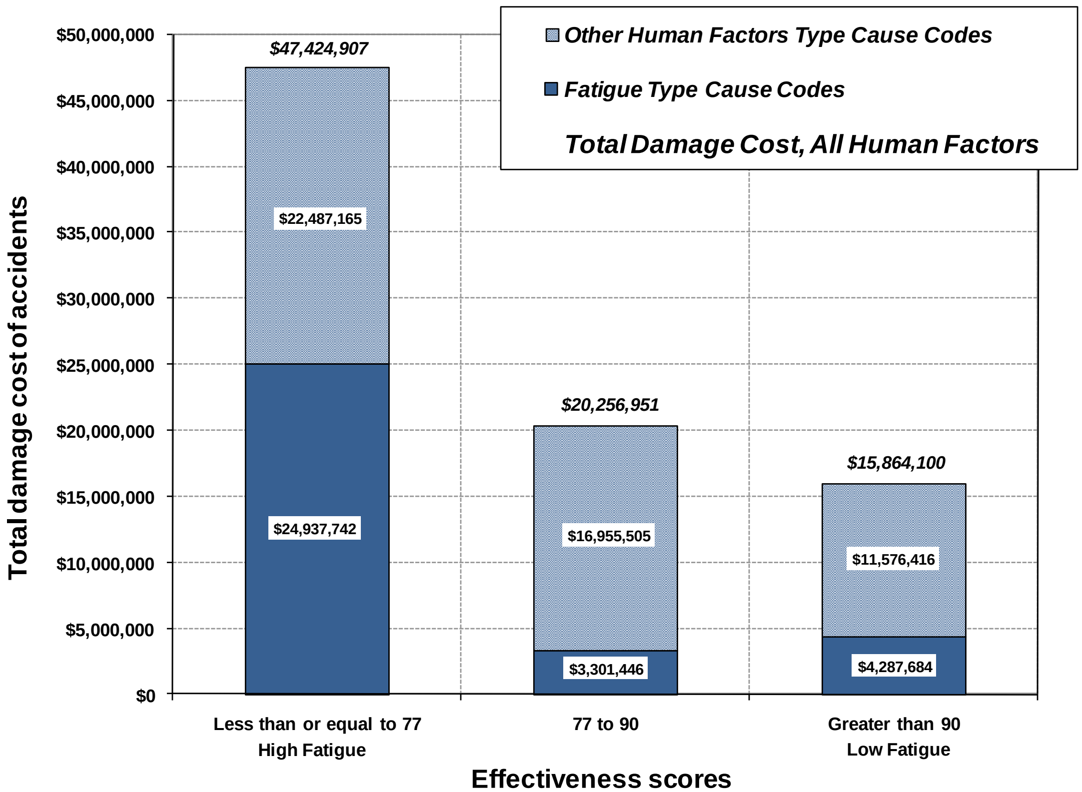

Figure 2. Total Cost of HFs-Related Accidents in Three Disjoint Crew Effectiveness Score Intervals by Accident Type

Figure 3 presents the number of accidents in each interval, and, together with Figure 2, suggests that these particular types of accidents are especially costly: The 13 percent of HF-related accidents with fatigue type cause codes at scores above 77 account for 21 percent of all HF-related accident costs, whereas at 77 or below, the 26 percent of HF-related accidents that are attributable to these cause codes account for 53 percent of all HF-related accident costs.

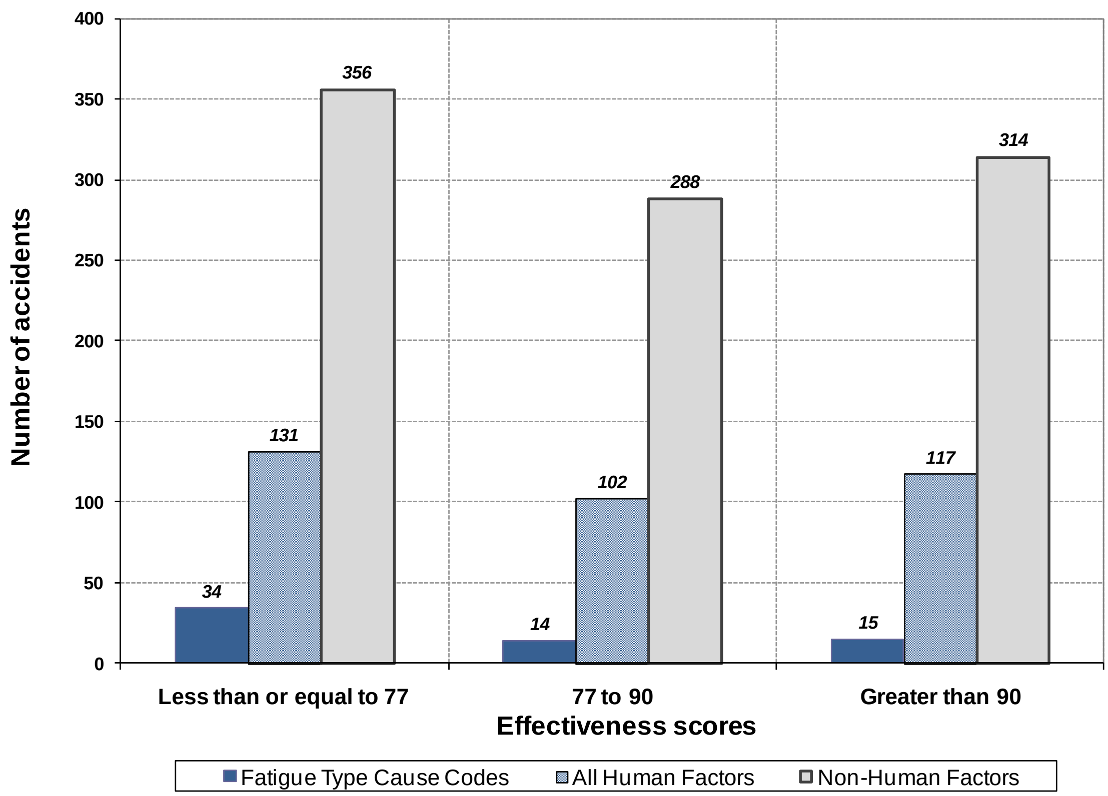

Figure 3. Number of Accidents in Three Disjoint Crew Effectiveness Score Intervals

Figure 4 (on the next page) dramatically highlights the situation: Although average NHF-related accident costs (light gray bars) are roughly equivalent among the intervals, HF-related accidents (blue checked bars) taken together show an increase in average accident damage cost of approximately 2.7 times between the highest effectiveness category (low fatigue) and the lowest effectiveness category (high fatigue). The average damage cost of accidents at or below 77 bearing fatigue-type cause codes (solid blue bars) are more than 2.5 times the cost of those of fatigue-type accidents in the highest intervals (low fatigue) and cost five times the average cost of all HF-related accidents above a score of 90.

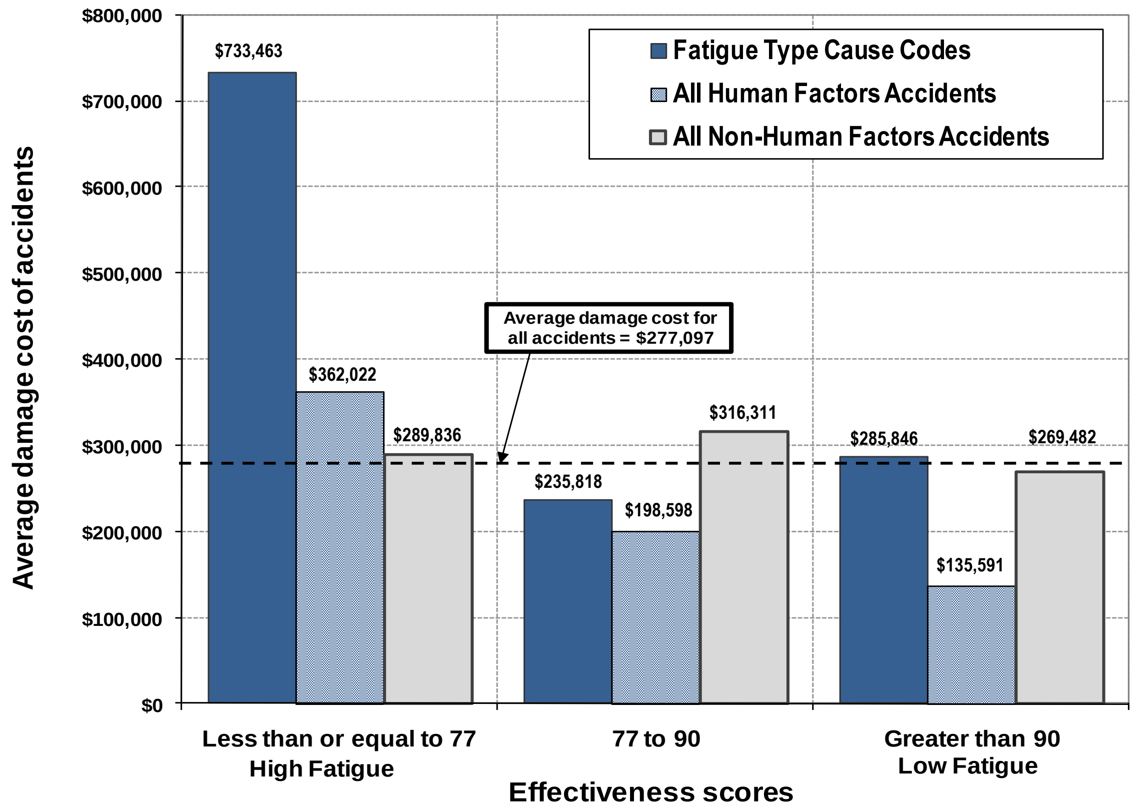

Figure 4. Average Accident Damage Cost in Three Disjoint Crew Effectiveness Score Intervals by Accident Cause Classification

3.4 Casualty Costs

Figure 2 and Figure 4 are based on accident costs that were limited to the financial impact of property damage as reported by the railroads to the FRA. A railroad accident can also incur costs in terms of casualties. Human injuries and/or death were reported to the FRA in 82 of the accidents analyzed in this study, including 15 fatalities and 408 cases of nonfatal human injury.

Including casualties in the total cost of an accident necessitated assigning a dollar cost to each instance of injury or death. Costs were assigned to each casualty on the basis of the MAIS, which runs from 1 (minor injury) through 6 (death) and associates each level with a cost as a fraction of the value of a statistical life (VSL),[8] which is estimated as $6 million in accordance with current DOT practice (see U.S. Department of Transportation, 2008).

Fatalities were set to an MAIS level of 6. The MAIS level for each nonfatal injury was estimated using the number of LWDs by the injured, reported in the FRA accident databases, using equation (1), rounded to the nearest whole number, with a minimum value of 1 and a maximum value of 5.[9]

[8] A description of MAIS levels with corresponding injuries and the associated VSL fraction are included as Appendix A, Table 2.

[9] See Appendix A for the derivation of the equation relating LWD to MAIS level.

$$\text{MAIS level} = 0.031 \times (\text{LWD}) - 0.37. \quad (1)$$

Finally, for each accident, the estimated costs for all casualties were summed and added to the accident damage cost, yielding an estimated total cost for the accident. We added these casualty costs to the damage costs shown in Figure 2 and obtained the total accident cost values shown in Figure 5. The casualty costs of accidents (dark blue bars) decreased with increases in effectiveness and reductions in fatigue. For accidents with average operator effectiveness at or below 77, casualty costs are more than triple the property damage costs. Total cost of accidents in that range was over $200 million compared with total cost of $46 million for accidents above an effectiveness score of 90.

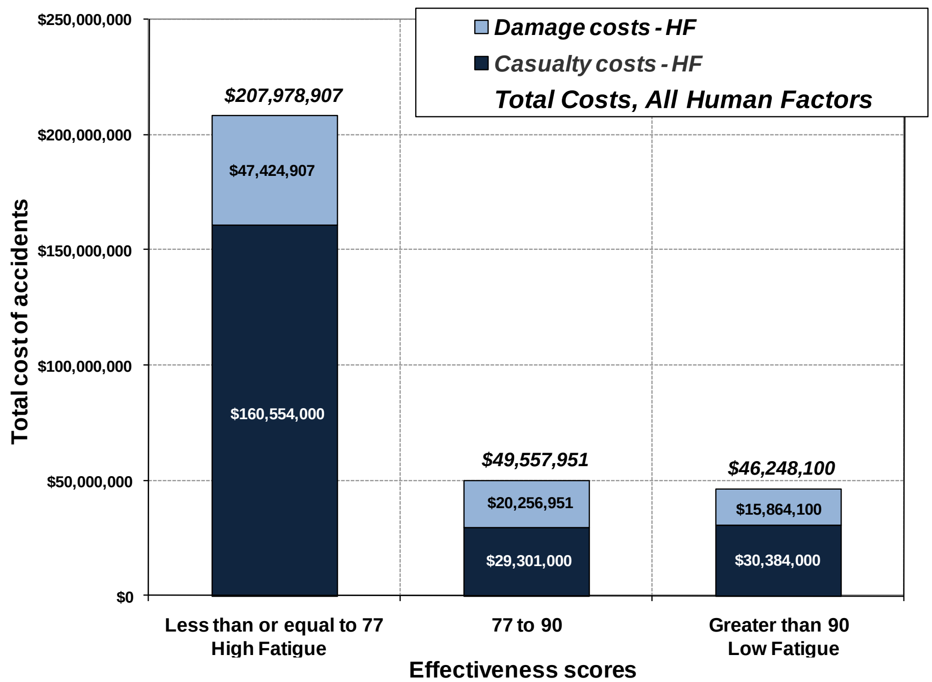

Figure 5. Total Accident Cost ($) from Casualties (dark blue) and Property Damage (light blue) Associated with HFs-Related Accidents as a Function of Average Operator Effectiveness

As one might expect, then, average accident cost decreases with increasing effectiveness, shown in Figure 6. Average accident cost, including casualty costs, was approximately $1.6 million when average operator effectiveness was at or below 77, compared with about one-quarter of that value (approximately $400,000) when average effectiveness was above 90. The average cost of HF accidents between 77 and 90 was very nearly equal to the overall average cost of HF accidents, or approximately $485,000.

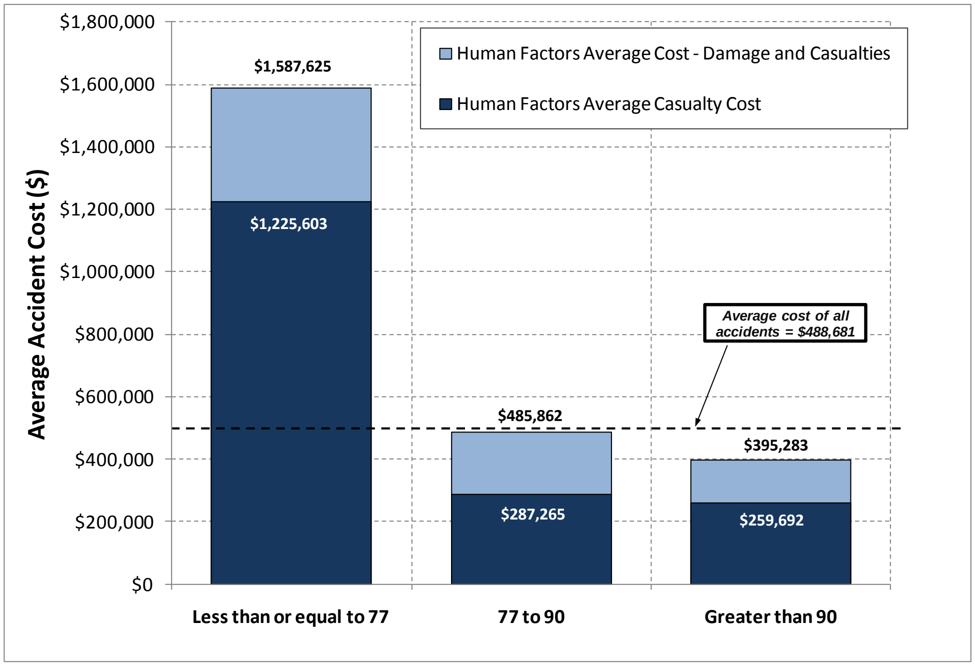

Figure 6. Average Total Accident Cost ($) from Casualties (dark blue) and Property Damage (light blue) Associated with HFs-Related Accidents as a Function of Average Operator Effectiveness*

*Overall mean accident cost is shown as the horizontal dashed line.

3.5 Relative Risk of Accidents and Cost

Figure 7 presents the results of applying the discussion of relative risk in Section 2.1.4 to HF-related accident cost data in these intervals. Estimates of the relative risk of accident occurrence and of damage cost began with the work histories for 30 calendar days prior to an accident provided by the participating railroads for each crew member on duty aboard the train involved at the time of the accident. Processing these work histories with the FAST Batch software generated estimates of each crew member's sleep patterns and an estimated effectiveness score for each half-hour time slice of each work shift, including an estimate of individual effectiveness at the time of the accident. The half-hour intervals were allocated to the effectiveness score intervals where the estimate fell.

Crew harmonic mean effectiveness scores at the time of the accident were computed from individual crew members' estimated effectiveness, as described in Section 2.2.1 above, and the accidents were allocated among the three effectiveness score intervals by the resulting scores. Risk of an HF-related accident in each of the three effectiveness score intervals was estimated as the ratio of the fraction of such accidents with crew effectiveness scores in that interval divided by the fraction of half-hour intervals across all crew members with estimated effectiveness scores in the same interval. This is the risk value computed in the prior report (Hursh et al., 2006, 2008).

The *relative* accident risk was then computed as the ratio of this value divided by the risk of an accident with a crew effectiveness score that was found in either of the other intervals. The relative economic risk was computed in the same fashion, except that each accident was weighted (multiplied) by its cost. In the subsequent graphs, we convert the fractional value to a percent; 100 percent is an unchanged relative risk, a value of 200 percent represents a doubling of relative risk, and a value of 70 percent represents a 30 percent reduction in relative risk.

Figure 7 shows the results of this effort. The risk of an HF-related accident is estimated to increase by 42 percent for crew effectiveness scores of 77 or below, relative to the risk when crew effectiveness scores are above 77. That is, the frequency of HF-related accidents is 42 percent greater when the crew effectiveness scores are 77 or lower versus when they are higher. In contrast, relative accident risk is reduced by 30 percent when crew effectiveness scores are above 90, and virtually unchanged (+3 percent) in the intermediate range.

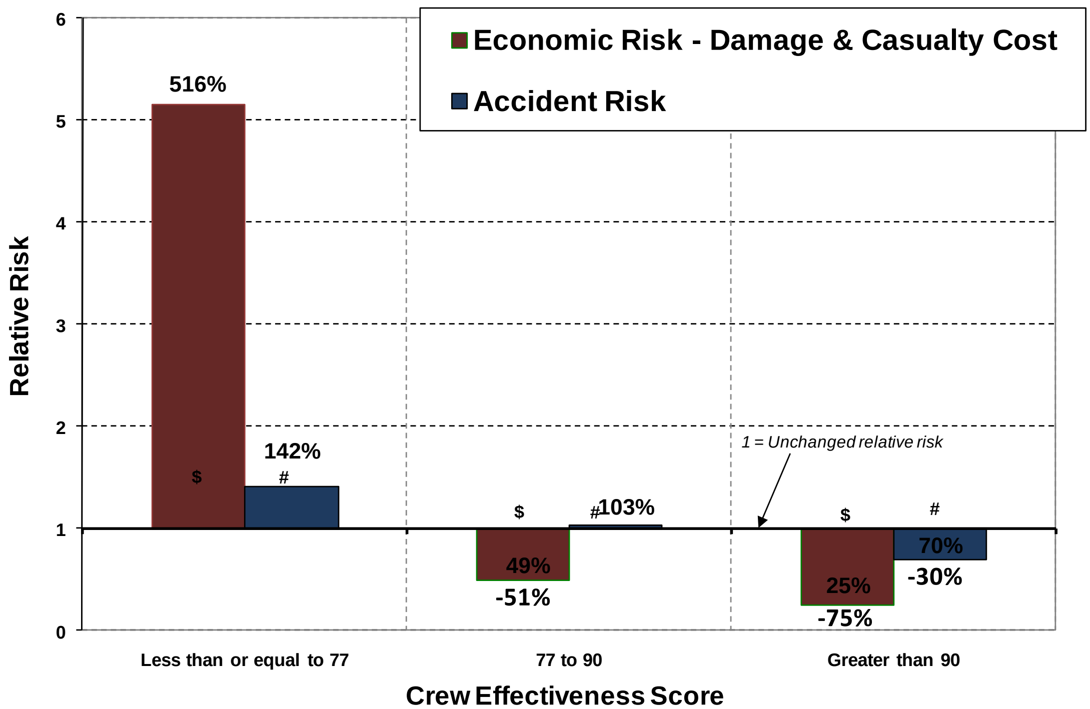

Figure 7. Relative Accident Risk (blue bars) and Relative Economic (damage and casualty cost) Risk (red bars) Associated with HFs-Related Accidents*

*For relative risk values less than 100 percent, we also show the change in risk by subtracting 1 (i.e., risk reduction).

More drastically, the relative economic risk—relative accident risk multiplied by the corresponding average cost of an HF-related accident (damage cost and casualty cost combined)—is estimated to be more than *five times higher* (516 percent) when crew effectiveness scores are at or below 77 compared with when crew effectiveness is above 77. At the other end of the continuum, relative economic risk is *reduced by a factor of 4 (–75 percent)* when crew effectiveness is above 90, relative to when crew effectiveness is below 90. In the middle of the effectiveness range, between 77 and 90, relative economic risk is reduced by 51 percent.

3.6 Total Accident Cost Relative to Effectiveness Scores

The analysis that was conducted for Figure 1 was repeated with the costs of casualties included to see if these added costs altered the threshold for maximal difference in cost between fatigue associated and non-fatigue-associated accidents. Figure 8 is the same analysis as shown in Figure 1 but with casualty costs included.

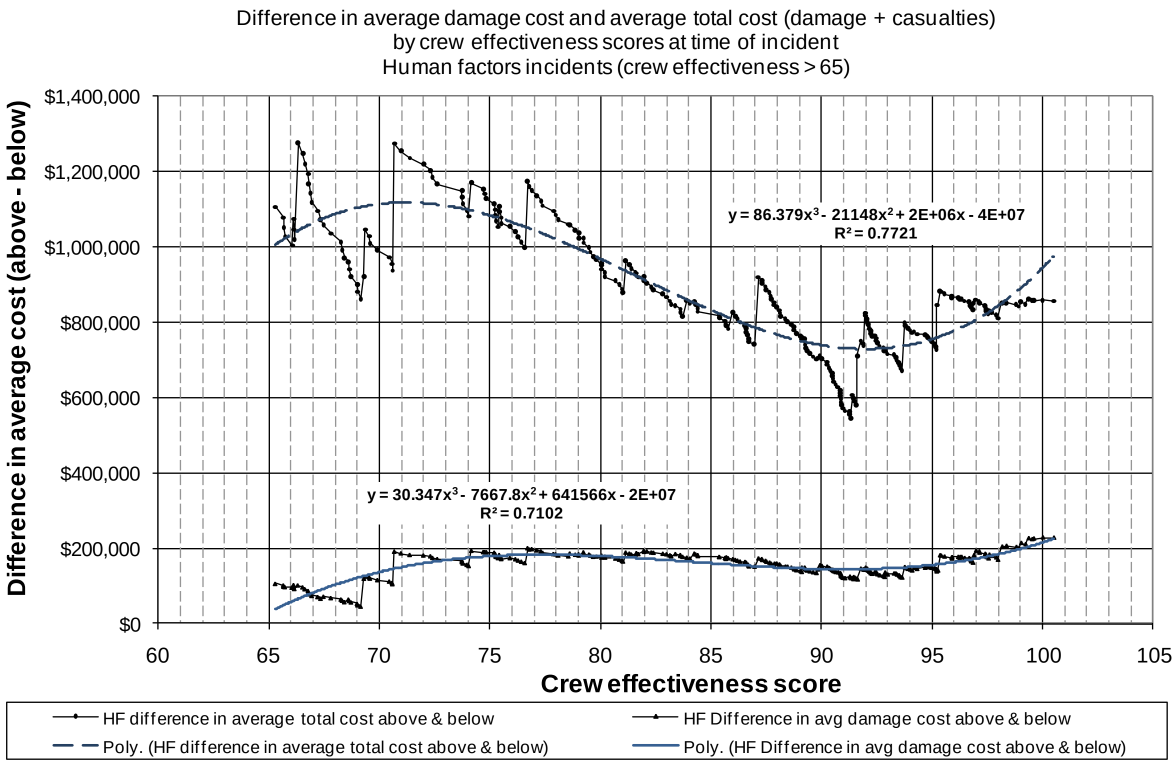

Figure 8. Difference in Mean Accident Cost Including Casualty Cost between HFs-Related Accidents at or below a Given Crew Effectiveness Score and Those above the Same Score with Cubic Polynomial Fit (blue line)

The upper line of the graph includes casualty costs and the lower data graph does not include casualty costs (as in Figure 1). Now it is clear that the point of maximal difference in accident cost shifts closer to 70 and the point of minimal difference remains close to 90. Of course, the new graph also shows the increase in total cost difference, reaching a maximum of approximately $1.1 million for accidents near 70. We, therefore, repeated the main cost analysis with these boundaries since FRA is considering a level of 70 as a threshold for examining fatigue under proposed new hours of service regulations.

3.6.1 Accident Cost with Effectiveness Less than 70

The effectiveness categories used in the preceding figures were chosen to maximize the differentiation between costly and less costly accidents based on the analysis shown in Figure 1. The cutoff score chosen to differentiate high fatigue from lower fatigue was 77. However, for regulatory purposes, a score of 70 would represent a hazard that creates a sufficiently high risk that it should be mitigated, based on the fatigue model calibration study reported previously (Hursh et al., 2006, 2008). It is, therefore, important to understand the economic benefit of reducing such extreme cases of fatigue using appropriate fatigue mitigation methods. The prior analysis was repeated with a lowest category set with an upper bound of 70. Figure 9 shows the average cost of HFs accidents (property damage and casualties) when average operator effectiveness was at or below 70. The average of total cost of accidents at or below 70 is nearly identical to the average cost of accidents at or below 77. However, the average cost of accidents in the large category from 70 to 90 now includes some higher valued accidents and increases to approximately $770,000. Overall, the trend line indicates that the total cost of accidents decreases exponentially as effectiveness increases from below 70 to above 90.

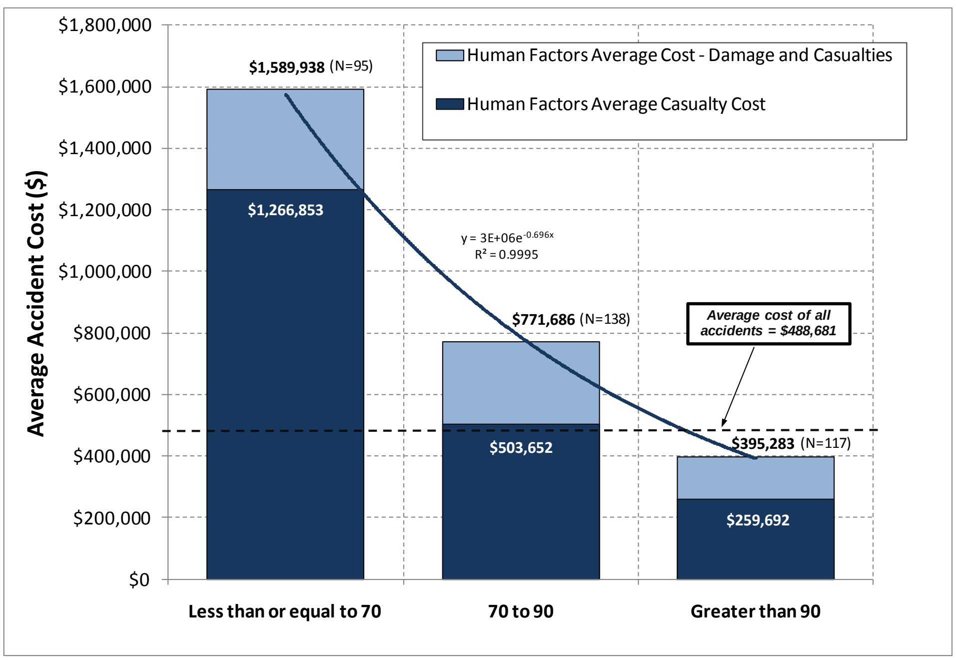

Figure 9. Average Total Accident Cost ($) from Casualties (dark blue) and Property Damage (light blue) Associated with HFs-Related Accidents as a Function of Average Operator Effectiveness*

*Overall mean accident cost is shown as the black horizontal dashed line. The number of accidents (N) in each category is indicated in each panel.

Dividing the effectiveness dimension into two categories, accidents at or below 70 and accidents above 70, indicates that accidents at or below 70 when fatigue is likely to be high are approximately 2.65 times more costly (damage plus casualties) than accidents above 70 when fatigue is not high, shown in Figure 10. Most of this difference can be attributed to the greater cost of casualties when fatigue is high (effectiveness is at or below 70).

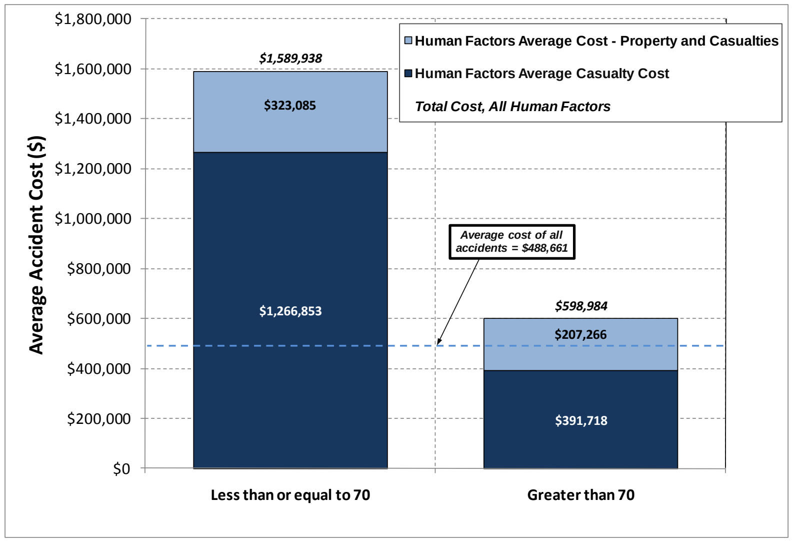

Figure 10. Average Total Accident Cost ($) from Casualties (dark blue) and Property Damage (light blue) Associated with HF Accidents as a Function of Average Operator Effectiveness*

*Overall mean HF accident cost is shown as the black horizontal dashed line.

3.6.2 Statistical Test of Accident Cost Relative to Effectiveness of 70 or Below

It is reasonable to ask if the differences in average accident cost shown in Figure 10 are statistically significant. However, subjecting the average accident cost to standard parametric tests based on an underlying normal distribution is not justified, since the observed distribution of accident costs in distinctly nonnormal; a relatively small number of costly accidents disproportionately affects the mean.

Instead, we investigated whether the proportion of costly HF accidents when the crew effectiveness score was equal to or less than 70 was significantly different from the proportion when crew effectiveness was over 70. We defined high cost accidents as ones with a total value greater than $80,000, which is approximately twice the overall median cost of all HF accidents of $39,913. We classified all HF accidents by costliness and crew effectiveness into a 2x2 contingency table, see Figure 11, finding 84 high-cost accidents among 255 accidents with crew effectiveness scores above 70 (33 percent) and 42 high-cost accidents among the 95 accidents with crew effectiveness scores equal to or below 70 (44 percent). We analyzed the relationship between costliness and crew effectiveness scores using Fisher's exact test for association.

This test found that if there were no association between cost and crew effectiveness, the probability of seeing purely by chance at least this large a difference in the fraction of high-cost accidents was 0.015. In other words, the proportion of high-cost accidents for crew effectiveness scores above 70 was significantly lower than that for crew effectiveness scores equal to or below 70 at the 98.5 percent level. In addition, just considering the proportion of high-cost accidents association with effectiveness less than or equal to 70, the probability was 0.035. Therefore, the relationship between low effectiveness (less than or equal to 70) and the disproportionate number of high cost accidents (greater than $80,000) was statistically significant ($p < 0.04$). These findings are summarized in Figure 11.

	70 or Less	Greater than 70
Greater $80K	42	84
Less or Equal $80K	53	171
% Greater than $80K	44%	33%

P = 0.015 (Fisher's exact test)

For 70 or less, Prob >= 42: 0.035

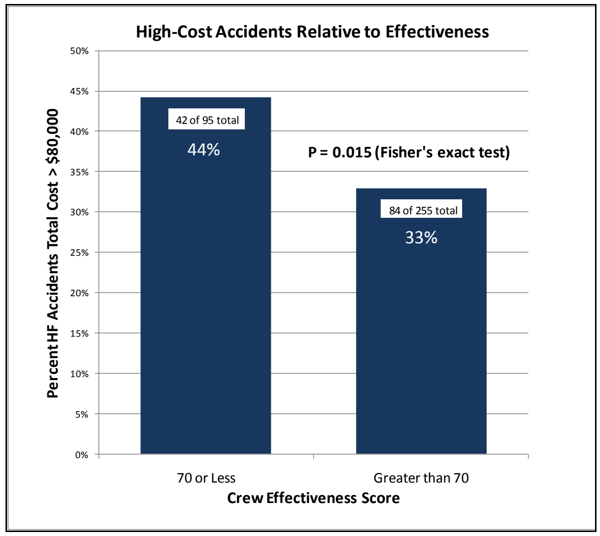

Figure 11. Proportion of HF Accidents with Total Cost Greater than $80,000 Relative to Crew Effectiveness Scores

3.6.3 Relative Risk and Relative Economic Risk for Effectiveness of 70 or Below

Recomputing relative risk values, Figure 12, with the lowest category starting at 70, indicates that accident risk is elevated 62 percent relative to being above 70, and relative risk of costs from damage and casualties is more than *quadrupled* when effectiveness is at or below 70 (430 percent). Relative risk of accidents between 70 and 90 is virtually identical to the risk at any other level of effectiveness and relative economic risk is 17 percent below the risk at other levels.

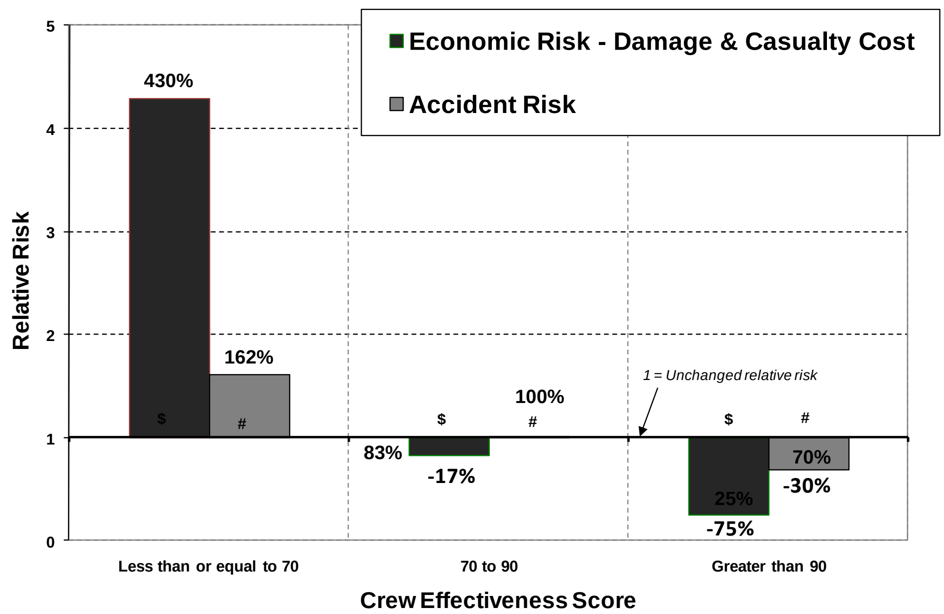

Figure 12. Relative Accident Risk (light gray) and Relative Economic (damage and casualty cost) Risk (dark gray) Associated with HFs

4. Conclusions

This report summarizes an economic analysis of 350 HF accidents and 958 NHF accidents reported by the five U.S. Class I freight railroads between 2003 and the first half of 2005. The cost of accidents in relation to model-estimated crew average effectiveness indicated that accident damage and casualty costs increased with reductions in predicted performance or increased fatigue. The pattern of results may be summarized as follows:

- The estimated relative economic risk (damage and casualty cost) of an HF-related accident is more *than quadrupled* when crew effectiveness scores are below 70.

- The estimated relative economic risk (damage and casualty cost) of an HF-related accident is *increased by a factor of five* when crew effectiveness scores are at or below 77 and *reduced by a factor of four* when crew effectiveness scores are above 90.

- The estimated relative accident risk of an HF-related accident is increased by 62 percent when crew effectiveness scores are at or below 70 and reduced by approximately 30 percent when crew effectiveness scores are above 90.

- The average total accident cost (damage and casualties) when crew average effectiveness is equal to or less than 70 (highly fatigued) is approximately $1.6 million, which is more than *triple* the overall average cost of accidents. In comparison to accidents without fatigue (when effectiveness is greater than 90), the average cost when crew average effectiveness is equal to or less than 70 is *quadrupled*. The average total cost of accidents decreases exponentially as effectiveness increases from below 70 to above 90.

- There was a statistically significant disproportionate number of high cost accidents (total value greater than $80,000) when crew effectiveness was equal to or less than 70.

- Taken as a whole, these results further validate the utility of using biomathematical fatigue models (here the SAFTE model and the FAST software) to estimate work related fatigue risk. Furthermore, the results calibrate the model to indicate that a score of 70 or below is associated with both an elevated relative risk and severity (cost) of accidents.

5. References

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Appendix A. Estimating the Cost of Casualties in Accidents Reported to the Federal Railroad Administration

Accidents that are required to be reported to the Federal Railroad Administration (FRA) include the cost of damage in dollars to infrastructure (track and permanent structures such as buildings or bridges) and equipment (railcars, locomotives, etc.), but do not provide a cost for casualties with the exception of fatalities. Fatalities have a defined cost of $6,000,000, often called the value of a statistical life (VSL). As a concrete example, consider a derailment that occurred on the Union Pacific Railroad on August 4, 2010. On the FRA Office of Safety Analysis Web Site (http://safetydata.fra.dot.gov/officeofsafety/) the cost of damage to infrastructure, number of deaths and injuries for this accident (UP20100810DV003) can be found in the Accident Detail Reports. The detail report indicates that there was $295,812 in equipment damage, $205,503 in track damage, 0 deaths and 3 injuries. The same accident can be queried in the Casualty Detail Reports, where the following detail about the three injuries is provided (Table 1):

Table 1. Example of injury data from the FRA Casualty Detail Reports

Example

Casualty #	Age	Job	Injury	Days Absent
1	57	Brakeman/Flagman	Multiple Bruises/contusions	2
2	36	Brakeman/Flagman	Multiple Bruises/contusions	0
3	44	Engineer	Multiple Bruises/contusions	0

Consequently, it is not possible to calculate the total cost of this accident or the vast majority of other accidents reported to FRA.

Currently, economic impact analyses that are required to document the benefits associated with the enactment of new regulations estimate the cost of casualties by reference to the MAIS (U.S. Department of Transportation Memorandum, February 5, 2008), which is shown in Table 2. Table 3 shows examples and descriptions of injuries for each of the MAIS levels. However, almost every injury can have more than one MAIS level. For example, concussions could be MAIS level 2 through MAIS level 5. In most accident reports there is little information for assigning a particular MAIS level to an injury. The difference between a concussion at MAIS level 2 and 5 is $4,482,000.

Table 2. The MAIS of the U.S. Department of Transportation

MAIS Level	Injury Severity	Fraction of VSL	Dollar Value
1	Minor	0.0020	$12,000
2	Moderate	0.0155	$93,000
3	Serious	0.0575	$345,000
4	Severe	0.1875	$1,125,000
5	Critical	0.7625	$4,575,000
6	Fatal	1.0000	$6,000,000

Table 3. Examples and Descriptions of Injuries for MAIS Levels

MAIS Level	Examples and Descriptions of Injuries
1	Superficial abrasion or laceration of skin, digit sprain, first-degree burn, head trauma with headache or dizziness (no other neurological signs).
	An AIS 1 injury is simple, and may not require professional medical treatment. Recovery is usually rapid and complete.
2	Major abrasion or laceration of skin, cerebral concussion (unconscious less than 15 min), finger or toe crush/amputation, closed pelvic fracture with or without dislocation.
	An AIS 2 injury almost always requires treatment but is not ordinarily life-threatening or permanently disabling.
3	Major nerve laceration; multiple rib fracture (without a flail chest); abdominal organ contusion; hand, foot, or arm crush/amputation.
	An AIS 3 injury has the potential for major hospitalization and long-term disability but is not generally life-threatening.
4	Spleen ruptures, leg crushes, chest wall perforations, and cerebral concussions with other neurological signs (unconscious less than 24 h). An AIS 4 injury is often permanently disabling, but survival is probable.
5	Spinal cord injury, extensive/deep laceration of kidney or liver, extensive second- or third-degree burns, cerebral concussions with severe neurological signs.
	An AIS 5 injury usually requires intensive medical care. Survival is uncertain.
6	One that will probably eventually lead to death, massive destruction of the cranium, skull, and brain.

The *FRA Guide for Preparing Accident/Incident Reports* (FRA, 2003) lists the injury and illness codes that are used in accident reports. This is shown in Table 4. Note that the codes are used in conjunction with body part location codes which are not in Table 4. The FRA Guide does not code severity of the injury. Table 4, however, shows the feasible range of MAIS levels that each injury might have, based on the examples and descriptions of injuries in Table 3. There are six injury codes (highlighted) that could reasonably have MAIS levels 1–5. These six codes epitomize the problem of assigning dollar values to injuries in the FRA accident reports.

Table 4. Nature of Injury Codes and Feasible MAIS Levels

		MAIS Level					
		Minor	**Moderate**	**Serious**	**Severe**	**Critical**	**Fatal**
NATURE OF INJURY	**Code**	**1**	**2**	**3**	**4**	**5**	**6**
Bruise or contusion	**10**	1					
Crushing Injury	**13**	1	2	3	4		
Sprain or strain	**20**	1	2				
Cut/laceration or abrasion	**30**	1	2				
Puncture wound (other than needle stick)	**35**	1	2				
Needle stick	**36**	1	2	3	4		
Electric shock or burn	**40**	1	2	3	4	5	
Other burns	**50**	1	2	3	4	5	
Dislocation	**60**		2				
Fracture (broken bone)	**70**		2	3			
Rupture/tear (tendon, cartilage)	**71**		2	3			
Gunshot, knife wounds	**72**		2	3	4	5	
Animal/snake/insect bite	**74**	1	2	3			
Dental related	**75**	1	2				
Amputation	**80**		2	3			
Fatatilly injured	**90**						6
Foreign object in eye	**91**	1	2				
Hernia	**92**		2				
Concussion/closed head injury	**93**	1	2	3	4	5	
Nervous shock (injury related)	**94**	1	2				
Internal injury	**95**			3	4	5	
Loss of eye	**96**				4		
Reaction from one-time external	**97**	1	2	3	4	5	
Symptoms due to one-time exposure	**98**	1					
Symptoms due to one-time	**9A**	1	2				
Medical removal (under OSHA requirements)	**9B**	1	2	3	4	5	
All other injuries	**99**	1	2	3	4	5	

An FRA report (Reinach and Gertler, 2001), *An Examination of Railroad Yard Worker Safety*, suggests a way to determine the average severity of various injuries. Table 16 of that report shows the number of LWDs (or days absent) and the number of injuries for the same injury codes listed in Table 4. Table 5 shows the mean number of LWDs per injury and the mean MAIS for each injury code based on Table 4. The same accident codes that were highlighted in Table 4 are highlighted in Table 5.

Table 5. LWDs, Number of Injuries, and Mean MAIS for FRA Injury Codes

Injury Code	Injuries	LDWs	LWDs per Injury	Mean MAIS
10	655	29533	45.09	1
13				2.5
20	2643	173355	65.59	1.5
30	296	11170	37.74	1.5
35	35	989	28.26	1.5
36				2.5
40	19	621	32.68	3
50	28	455	16.25	3
60	60	6336	105.60	2
70	396	26477	66.86	2.5
71				2.5
72				3.5
74				2
75	2	48	24.00	1.5
80	46	6450	140.22	2.5
90				6
91	59	165	2.80	1.5
92	56	3635	64.91	2
93	22	1472	66.91	3.5
94	1	167	167.00	1.5
95	7	905	129.29	4
96				4
97	19	271	14.26	3
98	7	267	38.14	1
9A				1.5
9B	25	1900	76.00	3
99	158	11166	70.67	3

Table 6 shows average accident cost as a function of MAIS level, based on Table 5. MAIS levels 3.5 and 5 do not have any LWD data, and LWD for MAIS level 6 would be infinity. It is also apparent in Table 6 that the mean LWD for MAIS 3 is an outlier. This is more easily seen in Figure 12, which plots MAIS as a function of mean LWDs. The red square is the MAIS level 3 datum. The remainder of the data are well-fit by a straight line (correlation coefficient = 0.965, $p < 0.01$).

Table 6. Mean LWD and MAIS Level

MAIS	LWD
1	41.6157
1.5	54.2301
2	85.2554
2.5	103.539
3	46.128
3.5	-
4	129.286
5	-
6	-

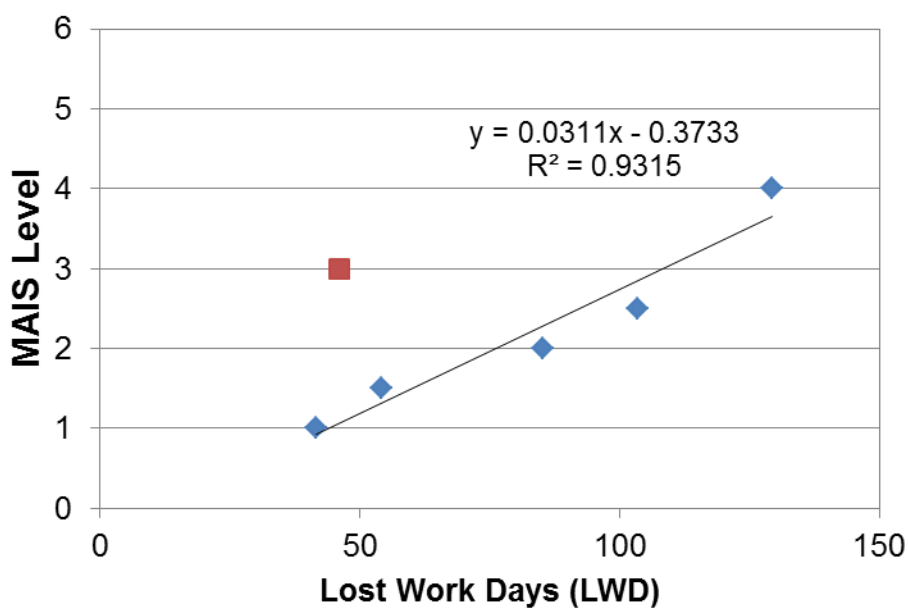

Figure 13. MAIS Level as a Function of LWDs

The best linear fit to the data is defined in equation (1):

$$\text{MAIS} = 0.031\ \text{LWD} - 0.373. \qquad (1)$$

With the equation (1), MAIS level can be estimated from LWD. Mathematically relating the cost of injuries to MAIS level from Table 2 is the next logical step. The relationship between MAIS and cost, however, is not mathematically tractable. The relationship is approximately a power function (r = 0.993), but the best-fitting line underestimates the cost of MAIS 5 by 34.4 percent. At MAIS 5, the true cost is $4,575,000, but the cost predicted by a power function is only $3,000,000.

An alternative is to construct a look-up table based on the true values and values interpolated for intermediate MAIS levels. This is presented in Table 7. For the economic analysis of accident costs related to estimate effectiveness level and fatigue, equation (1) was used in conjunction with the VSL levels in Table 1, rounding off levels to the nearest whole number. On the basis of Table 7, this approach may underestimate injury costs in some categories but is efficient when applied across this large data set.

Table 7. MAIS Level and LWDs

Expanded MAIS	Fraction of VSL	Dollars	LWDs
1	0.002	$12,000	46.82482
1.25	0.005375	$32,250	54.31657
1.5	0.00875	$52,500	61.80832
1.75	0.012125	$72,750	69.30007
2	0.0155	$93,000	76.79182
2.25	0.026	$156,000	84.28357
2.5	0.0365	$219,000	91.77532
2.75	0.047	$282,000	99.26707
3	0.0575	$345,000	106.7588
3.25	0.09	$540,000	114.2506
3.5	0.1225	$735,000	121.7423
3.75	0.155	$930,000	129.2341
4	0.1875	$1,125,000	136.7258
4.25	0.33125	$1,987,500	144.2176
4.5	0.475	$2,850,000	151.7093
4.75	0.61875	$3,712,500	159.2011
5	0.7625	$4,575,000	166.6928
5.25	0.821875	$4,931,250	174.1846
5.5	0.88125	$5,287,500	181.6763
5.75	0.940625	$5,643,750	189.1681
6	1	$6,000,000	-

Abbreviations and Acronyms

FAST	Fatigue Avoidance Scheduling Tool
FRA	Federal Railroad Administration
HF	human factor
LWD	lost workday(s)
MAIS	Maximum Abbreviated Injury Scale
mph	mile(s) per hour
NHF	nonhuman factor
SAFTE	Sleep, Activity, Fatigue, and Task Effectiveness model
VSL	value of a statistical life