June 2024
Technical Memorandum: UCPRC-TM-2022-05

Rest Period Characteristics Under Highway Truck Traffic for Mechanistic-Empirical Designs of Asphalt Concrete Pavements

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Partnered Pavement Research Center (PPRC) Project 3.41 (DRISI Task 3200): Further Improvement and Implementation of ME Design Algorithms and Field Characterization

PREPARED FOR:

California Department of Transportation
Division of Research, Innovation and System Information
Office of Materials and Infrastructure Roadway Research

PREPARED BY:

University of California
Pavement Research Center
UC Davis and UC Berkeley

TECHNICAL REPORT DOCUMENTATION PAGE

1. REPORT NUMBER
UCPRC-TM-2022-05

2. GOVERNMENT ASSOCIATION NUMBER

3. RECIPIENT'S CATALOG NUMBER

4. TITLE AND SUBTITLE
Rest Period Characteristics under Highway Truck Traffic for Mechanistic-Empirical Pavement Designs

5. REPORT PUBLICATION DATE
June 2024

6. PERFORMING ORGANIZATION CODE

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8. PERFORMING ORGANIZATION REPORT NO.
UCPRC-TM-2022-05
UCD-ITS-RR-22-132

9. PERFORMING ORGANIZATION NAME AND ADDRESS
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10. WORK UNIT NUMBER

11. CONTRACT OR GRANT NUMBER
65A0628

12. SPONSORING AGENCY AND ADDRESS
California Department of Transportation
Division of Research, Innovation, and System Information
P.O. Box 942873
Sacramento, CA 94273-0001

13. TYPE OF REPORT AND PERIOD COVERED
Technical Memorandum
June 2019 to June 2021

14. SPONSORING AGENCY CODE

15. SUPPLEMENTAL NOTES
DOI: 10.7922/G2B56H2H

16. ABSTRACT
Fatigue cracking due to repeated truck traffic loads is the leading cause of failure of asphalt concrete pavement in many locations. Rest periods, referring to the time intervals between successive trucks, may allow for partial or full recovery from fatigue damage and in turn extend pavement fatigue life. This study examines the characteristics of rest periods using traffic data from 40 weigh-in-motion (WIM) stations installed on California state highways and evaluates their effects on pavement performance using a mechanistic-empirical simulation program, *CalME*. Truck traffic data were extracted from these WIM stations at selected periods throughout 2015. Rest periods, the probability distribution of rest periods, and quantiles of cumulative rest periods were calculated. Regression and statistical analyses of the 0.5 quantiles (i.e., median) of rest periods were also performed for different spectrum groups and seasons. It was found that rest periods are strongly correlated with the truck traffic volume regardless of the WIM station location or season. The actual rest periods based on the nonuniform truck traffic measured from the WIM data were found to be slightly shorter than the corresponding theoretical average rest periods for uniform traffic (ARP-UT), currently assumed in *CalME*, likely due to truck-following. This theoretical value assumes an equal time interval between trucks at all times. After comparing pavement performance with and without rest periods using *CalME*, it was found that rest periods have significant influence (a 30% difference) on pavement cracking. *CalME* simulations also show that the difference in pavement performance caused by the difference between the actual rest periods and the ARP-UT is minimal. Continued use of the ARP-UT is therefore recommended to account for the effect of rest periods in pavement design.

17. KEY WORDS
weigh-in-motion, rest period, mechanistic-empirical design, fatigue, truck-following, CalME

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19. SECURITY CLASSIFICATION (of this report)
Unclassified

20. NUMBER OF PAGES
36

21. PRICE
None

Reproduction of completed page authorized

UCPRC ADDITIONAL INFORMATION

1. DRAFT STAGE Final	2. VERSION NUMBER 1
3. PARTNERED PAVEMENT RESEARCH CENTER STRATEGIC PLAN ELEMENT NUMBER 3.41	4. DRISI TASK NUMBER 3200
5. CALTRANS TECHNICAL LEAD AND REVIEWER(S) Raghubar Shrestha	6. FHWA NUMBER CA243200

7. PROPOSALS FOR IMPLEMENTATION

(1) Rest period effect needs to be accounted for in mechanistic-empirical designs of flexible pavements.
(2) Calculating rest period assuming unform traffic in *CalME* is adequate.

8. RELATED DOCUMENTS

9. LABORATORY ACCREDITATION

The UCPRC laboratory is accredited by AASHTO re:source and CCRL for the laboratory testing discussed in this report.

10. SIGNATURES

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ACKNOWLEDGMENTS

This paper describes research activities that were requested and sponsored by the California Department of Transportation (Caltrans). This sponsorship is gratefully acknowledged. The authors thank Stan Norikane and Vicki Dickey at the Office of Traffic Operations in Caltrans for providing valuable support. The contents of this paper reflect the views of the authors and do not necessarily reflect the official views or policies of the State of California or the Federal Highway Administration. This paper does not represent any standard or specification.

PROJECT OBJECTIVES

The goal of this project is to gain more knowledge about pavement behaviors and to improve mechanistic-empirical (ME) design methods for California pavements so that Caltrans can accomplish its mission of building an efficient transportation system. This goal will be achieved though completion of the following tasks:

- Task 1: Identify ME design research needs.
- Task 2: Develop critical models for flexible pavements.
- Task 3: Develop critical models for rigid or composite pavements.
- Task 4: Develop critical models for generic pavements.
- Task 5: Implement improvements in ME design tools.
- Task 6: Update field characterization procedures.

This technical memorandum covers a portion of Task 2 listed above and is related to the modeling of fatigue damage of asphalt concrete to provide critical information for ME pavement designs of flexible pavements.

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LIST OF ABBREVIATIONS

ANOVA	Analysis of variance
ARP-UT	Average rest period for uniform traffic
CalME	California Mechanistic-Empirical design software for flexible pavement
CI	Confidence interval
ESAL	Equivalent single axle load
ME	Mechanistic-empirical
ODBC	Open Database Connectivity
SQL	Structured query language
tph	Trucks per hour
tphpl	Trucks per hour per lane
UCPRC	University of California Pavement Research Center
WIM	Weigh-in-motion

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
in.	inches	25.40	millimeters	mm
ft.	feet	0.3048	meters	m
yd.	yards	0.9144	meters	m
mi.	miles	1.609	kilometers	km
AREA				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.09290	square meters	m^2
yd^2	square yards	0.8361	square meters	m^2
ac.	acres	0.4047	hectares	ha
mi^2	square miles	2.590	square kilometers	km^2
VOLUME				
fl. oz.	fluid ounces	29.57	milliliters	mL
gal.	gallons	3.785	liters	L
ft^3	cubic feet	0.02832	cubic meters	m^3
yd^3	cubic yards	0.7646	cubic meters	m^3
MASS				
oz.	ounces	28.35	grams	g
lb.	pounds	0.4536	kilograms	kg
T	short tons (2000 pounds)	0.9072	metric tons	t
TEMPERATURE (exact degrees)				
°F	Fahrenheit	(F-32)/1.8	Celsius	°C
FORCE and PRESSURE or STRESS				
lbf	pound-force	4.448	newtons	N
lbf/in^2	pound-force per square inch	6.895	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimeters	0.03937	inches	in.
m	meters	3.281	feet	ft.
m	meters	1.094	yards	yd.
km	kilometers	0.6214	miles	mi.
AREA				
mm^2	square millimeters	0.001550	square inches	in^2
m^2	square meters	10.76	square feet	ft^2
m^2	square meters	1.196	square yards	yd^2
ha	hectares	2.471	acres	ac.
km^2	square kilometers	0.3861	square miles	mi^2
VOLUME				
mL	milliliters	0.03381	fluid ounces	fl. oz.
L	liters	0.2642	gallons	gal.
m^3	cubic meters	35.31	cubic feet	ft^3
m^3	cubic meters	1.308	cubic yards	yd^3
MASS				
g	grams	0.03527	ounces	oz.
kg	kilograms	2.205	pounds	lb.
t	metric tons	1.102	short tons (2000 pounds)	T
TEMPERATURE (exact degrees)				
°C	Celsius	1.8C + 32	Fahrenheit	°F
FORCE and PRESSURE or STRESS				
N	newtons	0.2248	pound-force	lbf
kPa	kilopascals	0.1450	pound-force per square inch	lbf/in^2

*SI is the abbreviation for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2021)

1 INTRODUCTION

Fatigue is often the main factor in the deterioration of asphalt concrete pavement where there is heavy vehicle traffic. It has long been known that not only the volume of heavy vehicles (trucks) traveling over pavement but also the intervals between arriving trucks, sometimes referred to as the "frequencies," influence the rate of fatigue damage over time. The time interval between the passing of two successive trucks over a location on a pavement is called the "frequency" in traffic operations, but this interval in terms of pavement damage is referred to as the "rest period" in this study *(1)*. Shorter rest periods do not allow asphalt concrete pavement to recover the temporary loss of stiffness when disturbed by a load (thixotropic) or provide time for microcracks to heal. The tensile strain is therefore greater in this softened condition when the next load passes, resulting in more permanent loss of stiffness (damage) and the faster appearance of fatigue cracking. Longer rest periods allow more recovery from the temporary loss of stiffness.

Laboratory measurements of the repeated loading of asphalt slabs on spring foundations first identified the beneficial effects of rest periods on fatigue life *(2)*. Subsequent research was conducted using a vibratory laboratory device and a loaded wheel testing machine, where the recovery of stiffness is also called "healing" *(3)*. Additional research showed the effects of rest periods in accelerated pavement testing *(4)*, and further laboratory testing *(5–7)* led to the recommendation of a shift factor of 20 from laboratory fatigue testing with no rest periods to field conditions *(8)* and the inclusion of rest periods in the 1985 *Shell Pavement Design Manual (9)*.

Continued laboratory experimentation and analysis improved the understanding of rest periods, including further examination of rest periods in terms of healing *(10)*, use of fracture mechanics testing and analysis instead of flexure *(11)*, and inclusion of healing in continuum damage mechanics *(12)*. Rest periods were used to explain differences between laboratory and accelerated pavement testing results and were included in the mechanistic-empirical (ME) design software *CalME (13)*. Consideration of healing for fatigue endurance limits (*14*), testing and explanation in terms of thixotropy *(14,15)*, and testing and analysis of binder thixotropic characteristics *(16)* have further improved understanding of the importance of rest periods.

Rest periods have also been the subject of more recent research *(17–19)*. The effects of shorter rest periods on asphalt pavement fatigue cracking performance will be dramatically increased when platooning trucks by using autonomous controls becomes fully feasible *(1)*.

This study uses California weigh-in-motion (WIM) data and ME simulation to investigate the influence of truck rest periods on asphalt concrete pavement structures. The California Department of Transportation (Caltrans) started installing WIM stations and collecting truck traffic data on state-owned highways in California in 1987. As of 2019, Caltrans owns and maintains 132 WIM stations on the California state highway network *(20)*. WIM devices instantaneously measure and record vehicle type, length, speed, gross vehicle weight, and axle load and spacing for each vehicle with the date and time stamp for each lane in each direction. The University of California Pavement Research Center (UCPRC) has worked with the California WIM data since 2002 *(21,22)*. Other researchers have also analyzed WIM data using various truck traffic study approaches and traffic inputs for ME pavement design in many states, including Louisiana, North Carolina, and Virginia *(23–25)*.

In 2019, the UCPRC analyzed the WIM data for 2003 to 2015, investigated similarities in axle load distributions at the WIM stations, and grouped them to generate traffic inputs for ME pavement design (*26*). Researchers developed a method that combined clustering and cut-tree analysis to create a decision tree to classify the WIM station data into five axle load spectra (Spectrum 1 through Spectrum 5) *(26)*. Spectrum 1 is the lightest axle load distribution, where the highest proportion, approximately 50%, of the single-counted axle (defined as the individual axle within an axle group—e.g., a tandem axle group is composed of two single-counted axles) loads are between 20 and 30 kN. Spectrum 1 includes 20% of California WIM stations. Spectrum 5 is the heaviest axle load distribution, where approximately 60% of the single-counted axle loads are between 60 and 80 kN. Spectrum 5 includes 18% of California WIM stations. Spectrum 3, which represents the medium axle load distribution, has approximately 55% of the single-counted axle loads between 20 and 40 kN. It is the most common type and includes 29% of California WIM stations.

CalME is an ME-based flexible pavement design and analysis program developed by Caltrans and the UCPRC and used by Caltrans, local agencies, and consultant engineers for design of new asphalt pavement and rehabilitation with asphalt. Rest periods are not used in laboratory fatigue testing when characterizing materials for *CalME (27)*. The effect of a rest period is instead accounted for in *CalME* through a laboratory-to-field damage shift factor that depends on the length of the rest period. To better understand the effects of rest periods and account for them in *CalME*, it is of paramount importance to delve into the characteristics of rest periods under real highway truck traffic. Therefore, the objectives of this study are to investigate rest periods for highway truck traffic and evaluate the rest period characterization in *CalME* simulations. The results will be beneficial to state agencies for any asphalt pavement ME design method as well as *CalME* users for flexible new pavement and rehabilitation design.

2 DATA SELECTION AND DESCRIPTION

A database was established on the UCPRC server from the previous studies conducted in 2019 (*26*). It includes all traffic data measured at the WIM stations in California between 2003 and 2015 as well as WIM ID, direction, and lane number. The data were chronologically tabulated on the UCPRC server and accessed through Structured Query Language (SQL). The spectrum group information of each WIM station was also stored separately on the server. The overall size of the database is approximately 2.5 terabytes.

Due to the size of the database, traffic information from selected periods was extracted to cover the characteristics of rest periods in different seasons of a year. In this study, rest periods were calculated for the first week of February, May, August, and November in 2015 to investigate differences across seasons. A total of 40 WIM stations were chosen because they were all active during the selected target periods and located across the state. These WIM stations, consisting of two-lane to ten-lane highways, were categorized based on their spectrum groups. Additionally, the database was filtered to exclude passenger cars (vehicle class ≤2 according to Caltrans vehicle classification system *[28]*).

3 ANALYSIS APPROACH

Rest periods were calculated and analyzed based on truck traffic data derived from the UCPRC database. A MATLAB script with Open Database Connectivity (ODBC) connection to the SQL server (UCPRC server) was developed to extract relevant traffic information from the database and then calculate the rest periods. The rest periods were calculated based on the number of trucks passing in each lane per hour. They represent the time interval (in seconds) between the steering axles of two adjacent trucks. The probability distribution of rest periods up to 400 seconds was then analyzed for the truck traffic per hour per lane. Quantiles of 0.25, 0.5 (median), 0.75, and 0.99 were then obtained based on cumulative rest periods for detailed analysis. The detailed calculation steps are as follows:

1. Extract spectrum group information of all the WIM stations from the UCPRC database.
2. Categorize these WIM stations based on their spectrum groups, and remove WIM stations that were inactive during the target periods.
3. Determine the beginning and ending time of the target period of the spectrum group, and then retrieve measured data for the active WIM stations one by one for the group for analysis.
4. Extract all the hourly traffic information at the WIM station and order it by time.
5. Filter out other unnecessary columns to reduce data size.
6. Sort the trucks based on the order of their lanes (lane numbers and directions) at the WIM station.
7. Calculate rest periods for two adjacent trucks in the same lane, and calculate the amount of truck traffic in that lane during that hour.
8. Count the frequency of occurrence for every rest period second (up to 400 seconds with one-hundredth of a second interval).
9. Calculate the probability of each rest period, and then calculate the cumulative distribution function of each rest period.
10. Calculate quantiles for 0.25, 0.5, 0.75, and 0.99 probabilities according to the cumulative distribution functions.

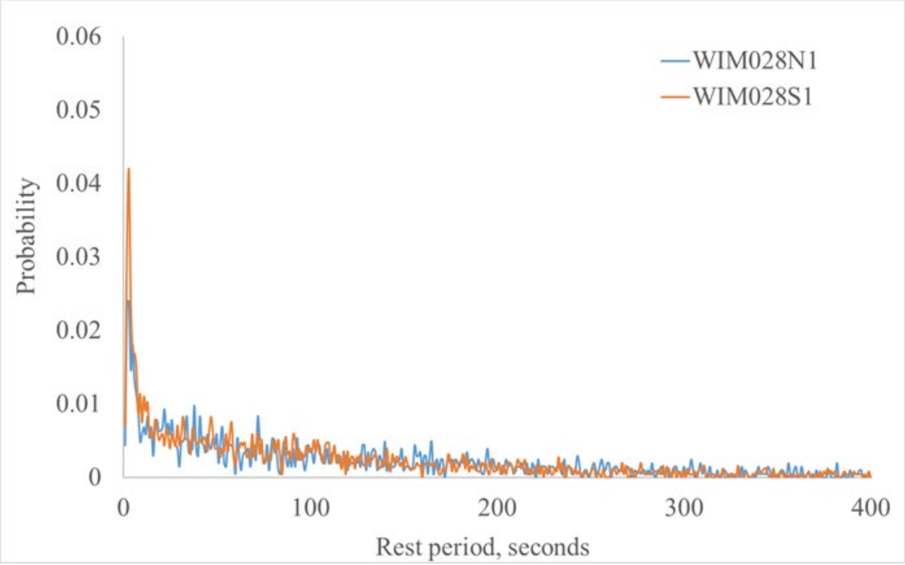
11. Repeat steps 4 to 10 for each hour of the selected analysis period for the WIM station.
12. Repeat steps 4 to 11 for the next WIM station in the same spectrum group, and summarize all the results in the Excel spreadsheet.
13. Repeat steps 3 to 12 for the next spectrum group.

4 RESULTS

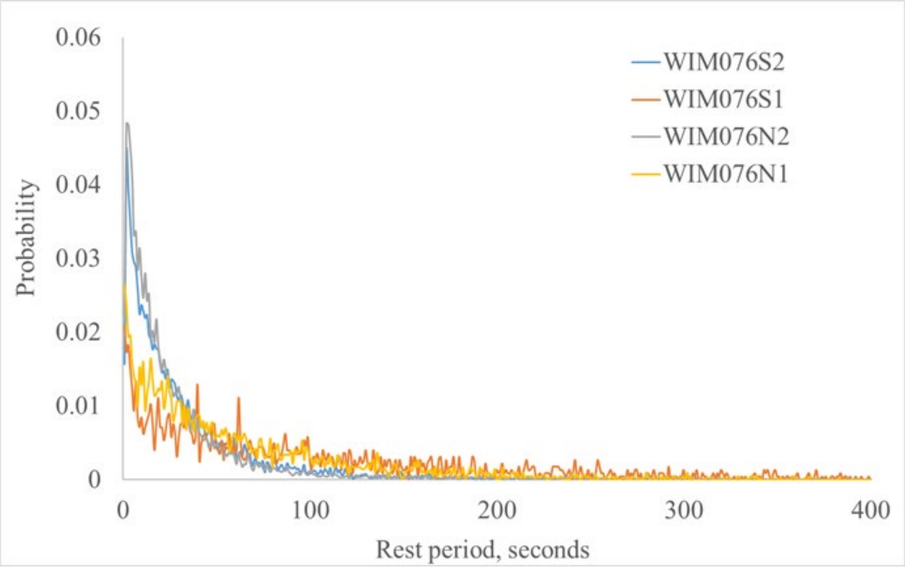
4.1 Probability Distribution of Rest Periods

The probability distribution of rest periods describes the likelihood of the interval time between passing trucks. Figure 4.1 shows as an example the probability distribution of rest periods from three WIM stations in the first week of February—from 7:00 a.m. on February 2 (Monday) to 11:59 p.m. on February 6 (Friday)—in 2015. There were no traffic data between midnight on Sunday and the early morning on Monday (7:00 a.m.). These WIM stations are installed on two-lane, four-lane, and six-lane roadways, and each WIM station has a different spectrum group classification. Figure 4.1 shows the probability distributions of rest periods, up to 400 seconds, for different lanes, and directions are shown for each type of roadway. It is evident that the probability of rest period distributions skew to the right with considerably long right tails. The most likely rest period was found to be about two to three seconds with the probability dropping rapidly after reaching the peak.

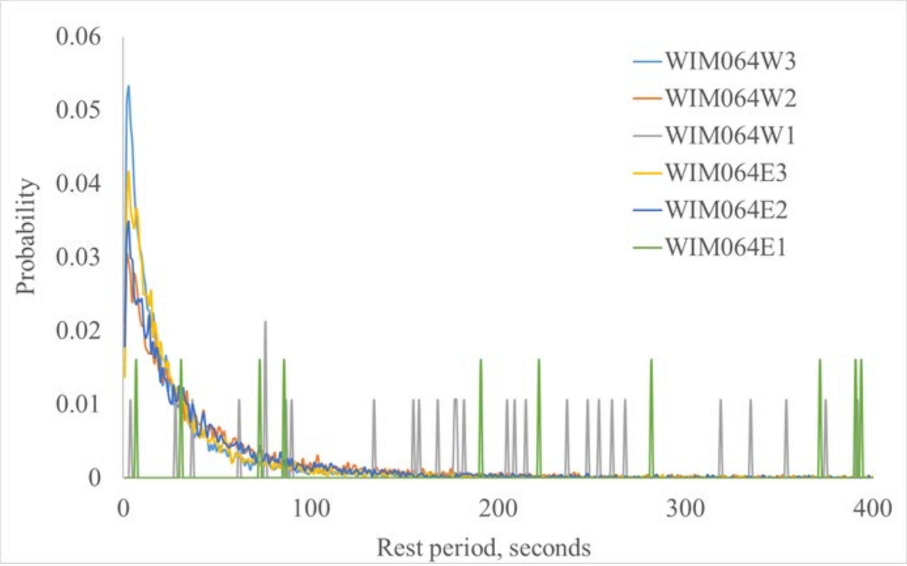
Truck traffic increases as the lane number increases (Caltrans numbers lanes from the inside to the outside). The outside lanes (i.e., the ones with higher lane number) exhibited higher probabilities for rest periods less than 40 seconds compared with the inside lanes. In a multi-lane roadway, the inside lanes usually tend to have minimal truck traffic. For example, WIM Station 064 had less than six trucks per hour in lane 1 in both directions) and, as a result, the probability distribution of rest periods can be random (e.g., Figure 4.1(c) for the distribution of rest periods for WIM064E1 and WIM064W1).



(a) A two-lane highway in Spectrum 5



(b) A four-lane highway in Spectrum 1



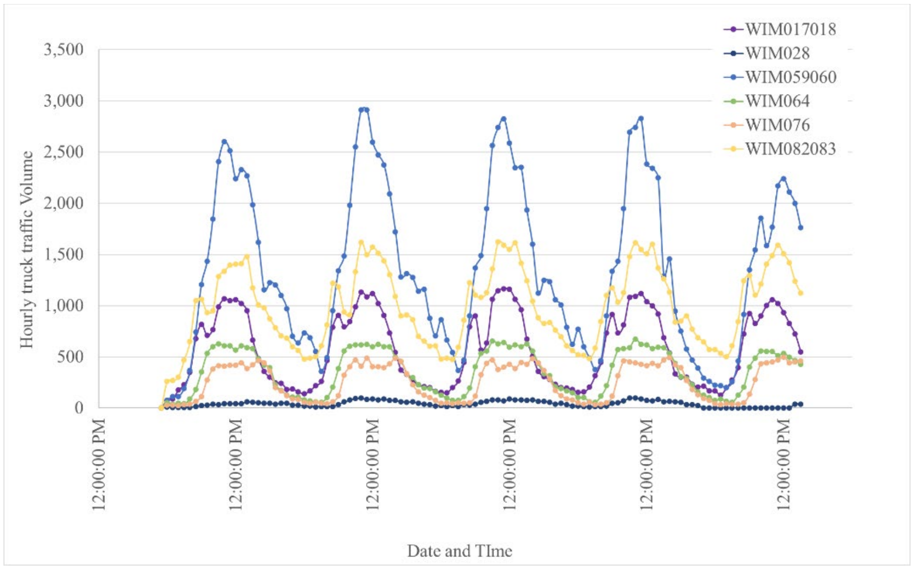
(c) A six-lane highway in Spectrum 2

Note: "N," "S," "E," and "W" denote northbound, southbound, eastbound, and westbound, respectively; "1," "2," and "3" denote lane number.

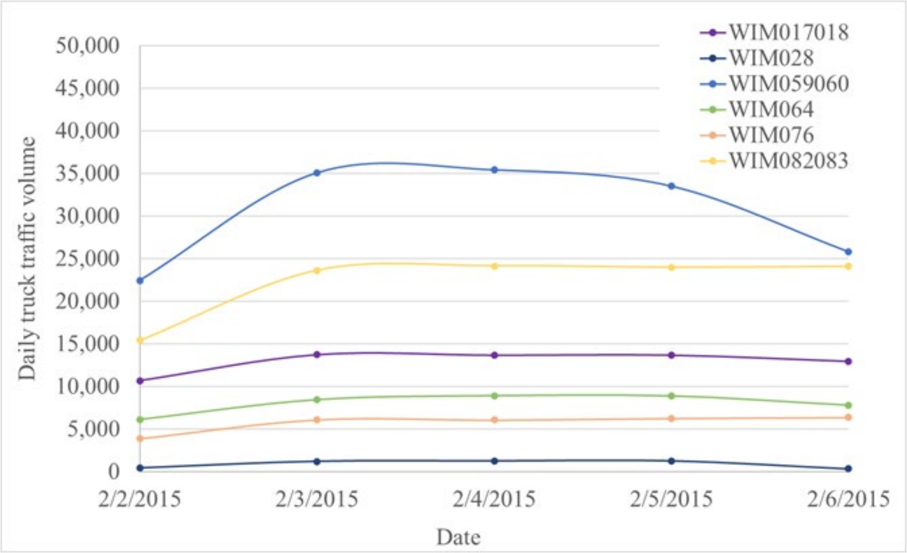
Figure 4.1: Examples of probability distribution of rest periods.

4.2 Distribution of Traffic Volume

A more detailed analysis of rest periods was performed hour by hour for each WIM station. Since traffic volume could affect the probability distribution of rest periods, hourly truck traffic volumes were calculated for each WIM station to determine the range of traffic levels as well as peak and off-peak hours. Figure 4.2 shows both hourly and daily truck traffic volumes for selected WIM stations during target periods. The maximum hourly truck traffic volume observed at these WIM stations was approximately 3,000 trucks per hour (tph), while the maximum hourly lane truck traffic volume was approximately 1,500 trucks per hour per lane (tphpl). The peak hours were from 10:00 a.m. to 2:00 p.m., depending on the WIM station locations. In terms of daily truck traffic volume, truck traffic volumes on Tuesday, Wednesday, and Thursday were higher than Monday and Friday. Between seasons, the truck traffic levels of other WIM stations did not differ significantly except for the WIM 082083 station.



(a) Example of hourly truck traffic volume



(b) Example of daily truck volume

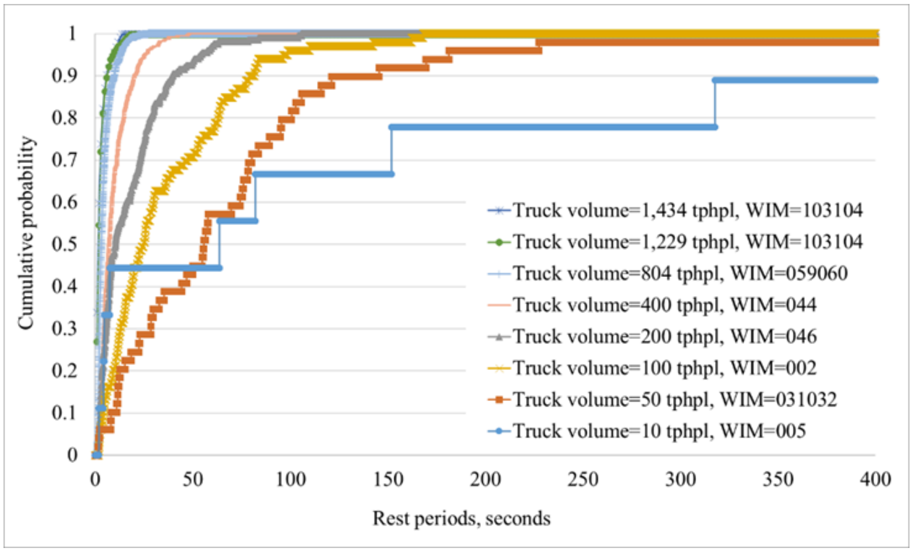
Note: WIM stations 017018, 059060, 082083 were combined WIM stations 017 and 018, 059 and 060, and 082 and 083, respectively.

Figure 4.2: Hourly and daily truck traffic volume in February 2015.

4.3 Analysis of Quantiles

To better compare the probability distribution of rest periods for different factors (e.g., truck traffic volume, WIM stations, lanes, directions, and time), quantiles were calculated based on the cumulative probability of rest periods for truck traffic for each hour and each lane. Figure 4.3

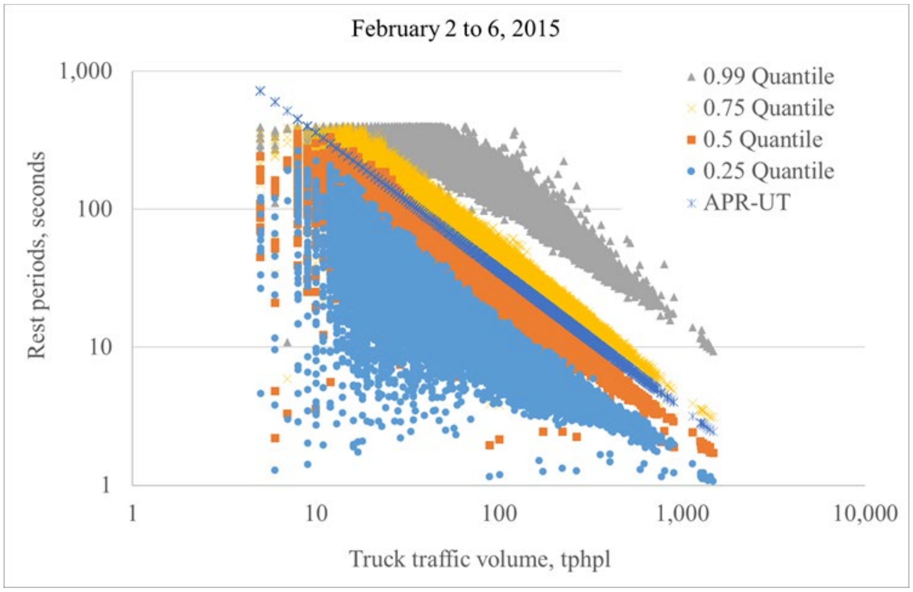
shows that the higher the traffic volume, the shorter the rest period, which is expected. It should also be noted that when truck traffic volume is low, the cumulative distribution is stepped (e.g., WIM station 005 with 10 tphpl). This result is due to the small sample population.



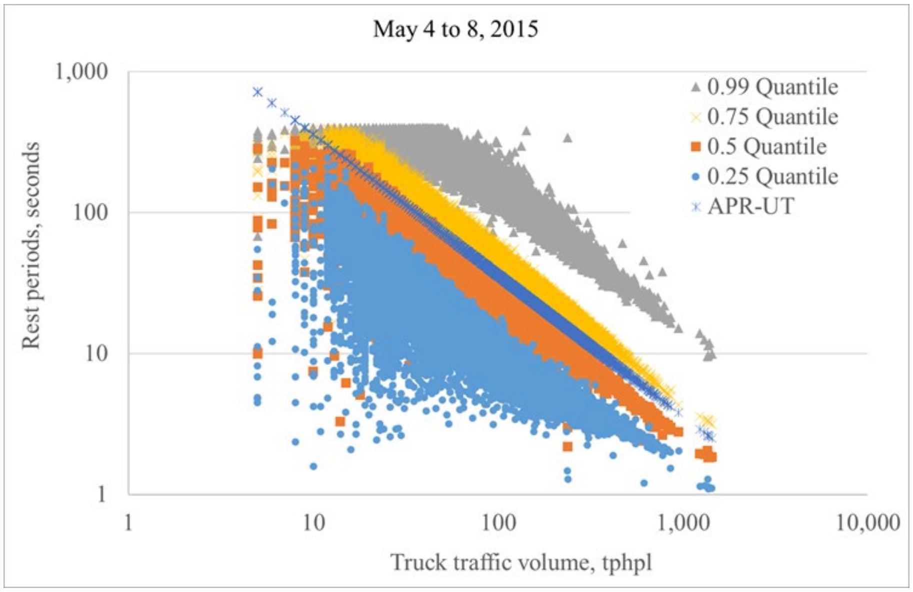
Note: tphpl = truck per hour per lane.

Figure 4.3: Cumulative probability for various truck traffic volume.

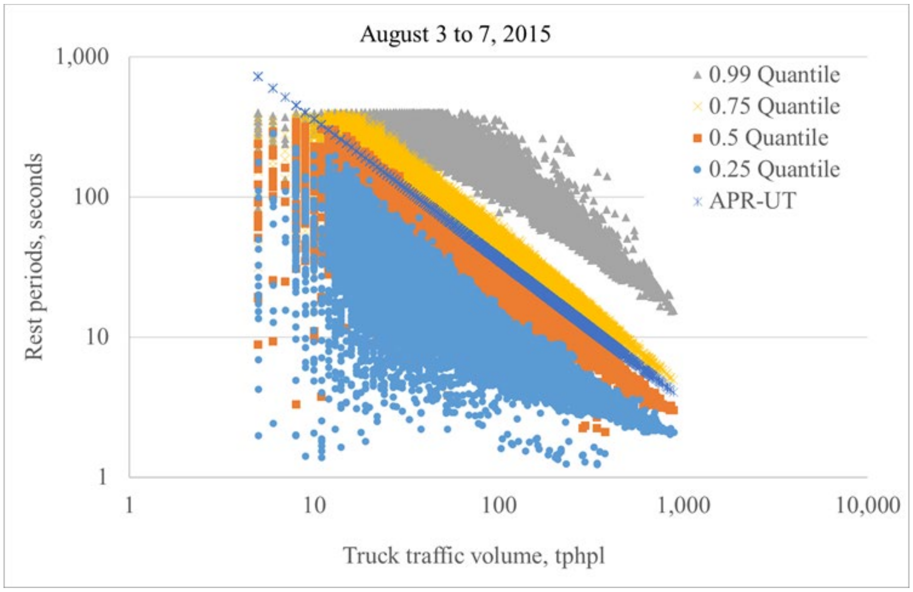
The 0.25, 0.5, 075, and 0.99 quantiles were then calculated as summary indices for cumulative probability for each hour, lane, and month, shown in Figure 4.4. The average rest periods for uniform traffic (ARP-UTs) were also obtained by dividing 3,600 seconds by the truck traffic volume per hour per lane. The ARP-UT is a theoretical value assuming an equal time interval between trucks all the time. Figure 4.4 indicates a linear correlation between rest period quantiles and hourly truck traffic volume in the logarithmic scale. It should be noted that some data were marked as outliers when linear regressions were conducted using these data, especially the ones with low traffic volumes. Compared with the 0.5 and 0.75 quantiles, the 0.25 quantiles and 0.99 quantiles show more variability. Additionally, both the 0.5 and 0.75 quantiles are close to the ARP-UT.



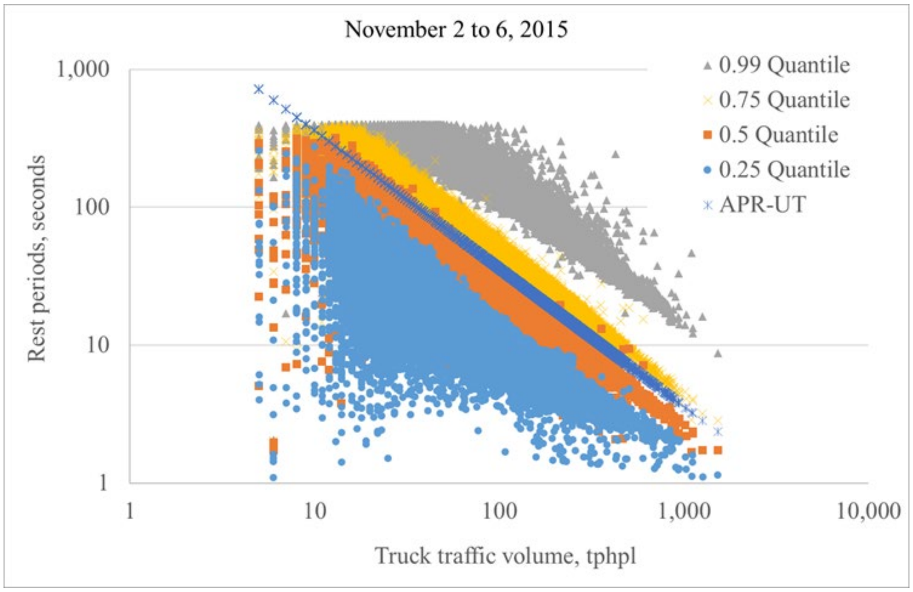
(a) Quantiles of rest periods for February 2015



(b) Quantiles of rest periods for May 2015



(c) Quantiles of rest periods for August 2015



(d) Quantiles of rest periods for November 2015

Figure 4.4: Example quantiles of rest periods in Spectrum 1 for different times in 2015 (February, May, August, November).

To compare rest periods for different quantiles levels, the average values of quantiles were calculated for each group of truck traffic levels. Figure 4.5 shows that the rest period decreases as traffic volume increases, as expected. In addition, various quantile levels from 0.05 to 0.99 and their corresponding overall average rest periods across all traffic levels were calculated for analysis. A polynomial function was proposed to estimate the rest period at a given quantile level, shown in Figure 4.6 as an example.

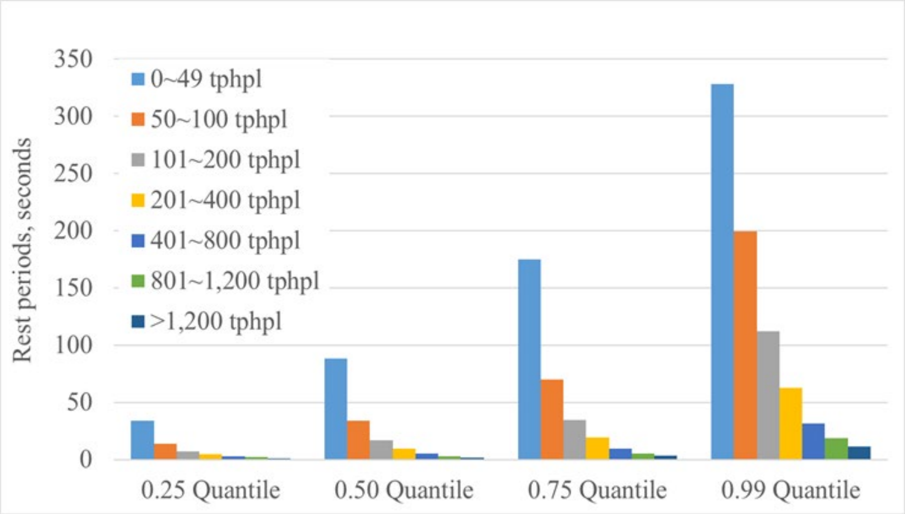


Figure 4.5: Average truck traffic quantiles for various traffic volume.

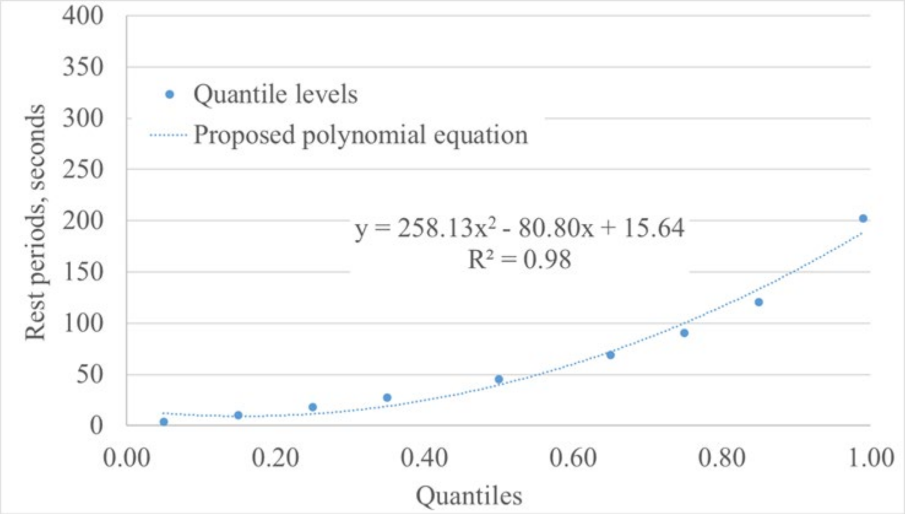


Figure 4.6: Correlation between overall average rest periods and quantile levels.

4.4 Regression Analysis

As previously discussed, the quantiles and hourly truck traffic volumes showed a linear relationship (Figure 4.4). As a result, a linear regression model (Equation 4.1) was applied to the 0.5 quantile since it was more suitable for comparison to the theoretical ARP-UT.

$$y = a * x + b \tag{4.1}$$

Where:

y = rest periods for 0.5 quantile in the logarithmic scale

x = truck traffic volume per hour per lane (tphpl) in logarithmic scale

a and b = model parameters

Table 4.1 to Table 4.4 summarize all the coefficients a and b determined from the linear regression model for the different spectrum groups and months of the year. The 95% confidence interval (CI) and R-squared values (R^2) were also determined. The differences between model parameters a and b seem to be very small, and an analysis of variance (ANOVA) was performed for verification.

Table 4.1: Summary of Linear Regression Results for the 0.5 Quantiles for February 2015

Spectrum	a	Lower 95% CI for a	Upper 95% CI for a	b	Lower 95% CI for b	Upper 95% CI for b	R^2
1	-0.887	-0.906	-0.867	3.166	3.132	3.200	0.902
2	-0.946	-0.954	-0.937	3.258	3.242	3.274	0.922
3	-0.950	-0.957	-0.943	3.270	3.256	3.284	0.949
4	-0.948	-0.965	-0.931	3.262	3.229	3.296	0.952
5	-0.930	-0.947	-0.913	3.203	3.172	3.234	0.886

Table 4.2: Summary of Linear Regression Results for the 0.5 Quantiles for May 2015

Spectrum	a	Lower 95% CI for a	Upper 95% CI for a	b	Lower 95% CI for b	Upper 95% CI for b	R^2
1	-0.916	-0.949	-0.883	3.214	3.156	3.271	0.861
2	-0.955	-0.964	-0.945	3.281	3.263	3.299	0.940
3	-0.940	-0.948	-0.931	3.248	3.231	3.264	0.953
4	-0.891	-0.917	-0.866	3.147	3.096	3.198	0.918
5	-0.946	-0.965	-0.926	3.226	3.189	3.262	0.910

Table 4.3: Summary of Linear Regression Results for the 0.5 Quantiles for August 2015

Spectrum	a	Lower 95% CI for a	Upper 95% CI for a	b	Lower 95% CI for b	Upper 95% CI for b	R^2
1	0.938	-0.953	-0.922	3.254	3.226	3.281	0.922
2	-0.945	-0.952	-0.938	3.262	3.249	3.274	0.934
3	-0.948	-0.953	-0.942	3.263	3.251	3.275	0.957
4	-0.915	-0.932	-0.898	3.190	3.156	3.224	0.929
5	-0.923	-0.935	-0.911	3.191	3.169	3.214	0.916

Table 4.4: Summary of Linear Regression Results for the 0.5 Quantiles for November 2015

Spectrum	a	Lower 95% CI for a	Upper 95% CI for a	b	Lower 95% CI for b	Upper 95% CI for b	R^2
1	-0.939	-0.955	-0.923	3.259	3.230	3.287	0.920
2	-0.924	-0.932	-0.916	3.216	3.201	3.232	0.902
3	-0.946	-0.953	-0.939	3.256	3.242	3.270	0.942
4	-0.915	-0.931	-0.900	3.191	3.161	3.222	0.943
5	-0.941	-0.955	-0.928	3.221	3.196	3.246	0.904

The ANOVA hypothesis testing was performed at a 95% confidence level to investigate whether the variation between means from various seasons found in the model parameters a and b is statistically significant. The null hypothesis and alternative hypothesis are the following:

$HO\colon \mu Feb = \mu May = \mu Aug = \mu Nov$

$Ha =$ Means are not all equal

Similarly, hypothesis tests were also performed at the 95% confidence level to determine whether the differences between means from the various spectrum groups found in the model parameters are statistically significantly different from the hypothesized differences between means.

The hypothesis testing results are summarized in Table 4.5. The conclusion was that there is not enough evidence to reject the null hypothesis, H_0, for both tests because P-values calculated were larger than 0.05. Hence, there is no statistically significant evidence at the 95% confidence level to show a difference in the means of coefficients a and b for different seasons and spectrum groups.

Table 4.5: Summary of ANOVA Results for Coefficients a and b Between Seasons and Spectrum Groups

Category	Coefficient	Source of Variation	Sum of Squares (SS)	DOF	Mean Square (MS)	F	P-value
Season	a	SSB	5.00×10^{-5}	3	2.00×10^{-5}	0.038	0.990
Season	a	SSE	6.99×10^{-3}	16	4.40×10^{-4}	N/A	N/A
Season	a	Total	7.04×10^{-3}	19	N/A	N/A	N/A
Season	b	SSB	2.50×10^{-4}	3	8.00×10^{-5}	0.050	0.985
Season	b	SSE	2.72×10^{-2}	16	1.70×10^{-3}	N/A	N/A
Season	b	Total	2.74×10^{-2}	19	N/A	N/A	N/A
Spectrum	a	SSB	2.71×10^{-3}	4	6.80×10^{-4}	2.342	0.102
Spectrum	a	SSE	4.33×10^{-3}	15	2.90×10^{-4}	N/A	N/A
Spectrum	a	Total	7.04×10^{-3}	19	N/A	N/A	N/A
Spectrum	b	SSB	1.17×10^{-2}	4	2.93×10^{-3}	2.798	0.064
Spectrum	b	SSE	1.57×10^{-3}	15	1.05×10^{-3}	N/A	N/A
Spectrum	b	Total	2.74×10^{-3}	19	N/A	N/A	N/A

Assuming no difference between seasons and spectrum groups, all the data was pooled together to develop an overall linear regression model for the 0.5 quantile, shown in Figure 4.7. Coefficient a is -0.935 with a 95% confident interval of (-0.937, -0.934) while coefficient b is 3.237 with a 95% confident interval of (3.234, 3.240).

Rest periods were also plotted to compare differences between estimated rest periods from the linear regression model and from the ARP-UT. As shown in Figure 4.7, there is an evident gap between the 0.5 quantile (median) rest period and the ARP-UT. This could be attributed to the truck-following phenomenon where a truck usually attempts to follow a leading truck in the same lane (*29*). A more detailed analysis of the truck-following phenomenon is discussed in the following section. Additionally, as expected, the differences decrease as traffic volume increases because high traffic volume will lead to more uniform traffic flow.

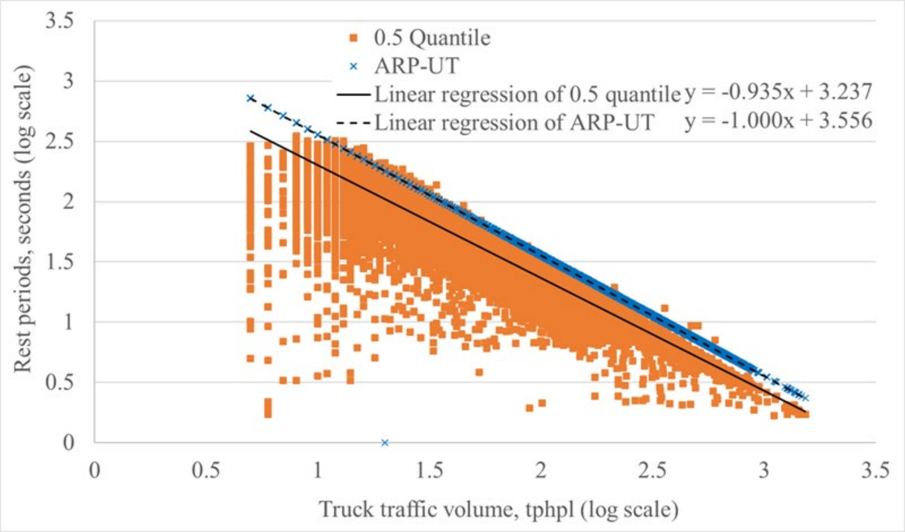
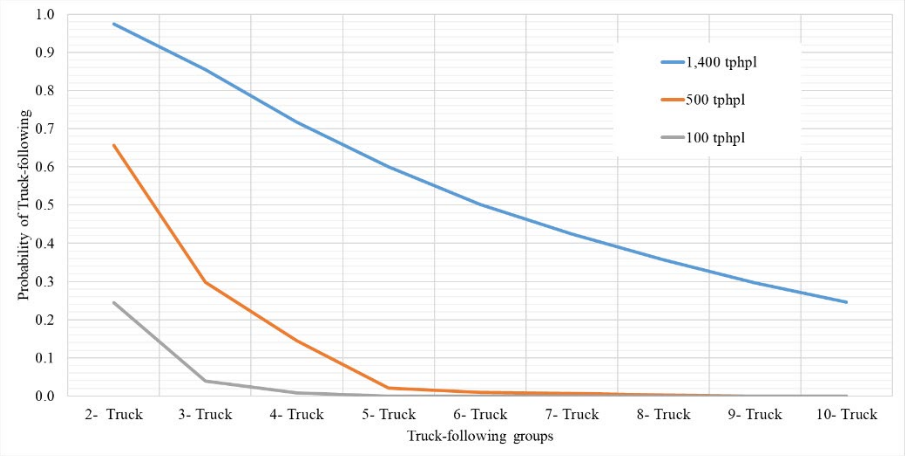


Figure 4.7: Linear regression model for 0.5 quantile of rest periods for all data.

4.5 Probability of Truck-Following

This section presents the probability of truck-following under various traffic conditions. Trucks tend to follow the leading truck in a group while maintaining a safe distance, when possible, to increase fuel efficiency and decrease interference with passenger vehicles on a truck lane (*28*). In this study, truck-following refers to two or more successive trucks voluntarily following with a rest period of less than four seconds. The rest period defined for truck-following, four seconds, was determined with consideration of a safe distance and the reaction time of a close-following truck, based on the *California Commercial Driver Handbook* (*30*). The probability of truck-following for various truck group sizes (e.g., two-truck group to ten-truck group) was calculated under three different traffic levels: (1) relatively low truck traffic level (100 trucks per hour per lane [tphpl], (2) medium truck traffic level (500 tphpl), and (3) relatively high truck traffic level (1,400 tphpl) in the WIM hourly data.

As shown in Figure 4.8, the average probabilities of a two-truck group under relatively low, medium, and relatively high truck traffic levels calculated from the selected five WIM stations were 0.24, 0.66, and 0.97, respectively. As a result, 97% of trucks either followed other trucks or were followed by other trucks at a relatively high hourly truck volume (1,400 tphpl). In contrast, only 24% of trucks either followed other trucks or were followed by other trucks when the hourly truck volume was relatively low (100 tphpl). As expected, the probability of truck-following decreased with increase in group size. At the relatively high truck traffic level, only 25% of the trucks formed a ten-truck group, and the average rest period between the two trucks was just 2.6 seconds. When the hourly truck volume was relatively low or medium, the percentage of trucks forming a four-truck or larger group was almost zero. Therefore, the portion of trucks forming truck-following groups is affected by truck traffic level and the size of the group. It is believed that truck-following is the reason why the median rest periods are usually shorter than the values calculated, assuming perfectly uniform truck traffic flow (Figure 4.8).



Note: tphpl = truck per hour per lane.

Figure 4.8: Probability of truck-following for different truck groups and truck traffic levels.

5 ACCOUNTING FOR EFFECT OF REST PERIOD IN PAVEMENT DESIGN

As shown in Figure 4.7, the 0.50 quantile (e.g., median) rest period is slightly lower than the ARP-UT. Specifically, the 0.50 quantile can be as low as 50% of the corresponding ARP-UT, which occurs when the truck traffic volume is low. Figure 5.1 shows the rest period for various quantiles normalized by the 0.50 quantile based on Figure 4.6. The 0.10 quantile is about 25% of the 0.50 quantile, which is 12.5% of the corresponding ARP-UT in the extreme cases (e.g., the traffic volume is low).

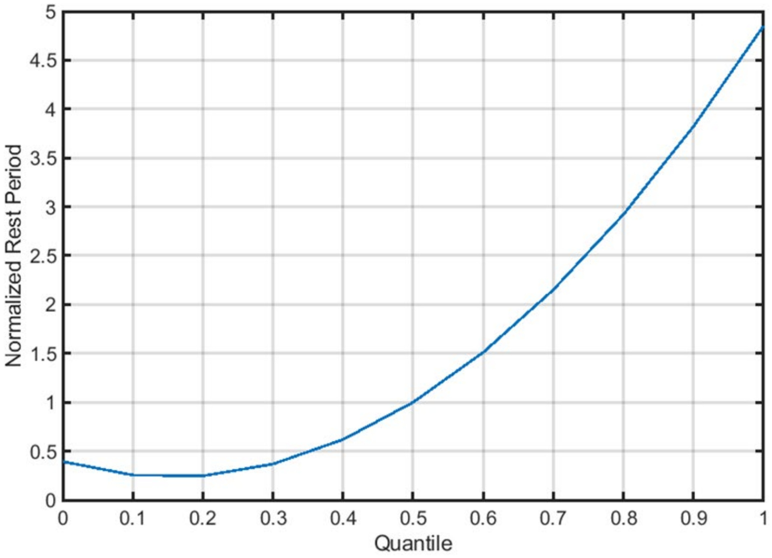


Figure 5.1: Normalized rest period for different quantiles.

A simple way to account for the effect of the rest period in pavement design is to assume truck traffic is uniform over time. This assumption is valid if the difference in performance using the actual rest period and the ARP-UT is minimal and can therefore be lumped into field calibration. While most ME pavement design methods do not account for the effect of rest period, *CalME* does account for this effect (see Wu et al. *[31]*) for the model) and it therefore is used to evaluate the effects of rest period on cracking performance.

Specifically, two pavements were designed using *CalME* for two different traffic levels—2 million ESALs and 20 million ESALs—over 20 years. The effect of rest period on the cracking performance for these pavements is listed in Table 5.1.

Table 5.1: Comparison of Cracking Performance of Selected Pavements

Structure	Relatively Thin	Relatively Thick
Design Traffic for 20 years (ESALs)	2 million	20 million
Non-HMA Layer Thicknesses[a]	HMA/150 mm (0.50 ft. AB)/ CL Subgrade[b]	Same
HMA Thickness	195 mm (0.65 ft.)	270 mm (0.95 ft.)
Cracking Life (Years) with ARP-UT	23.1 (100%)	20.5 (100%)
Cracking Life (Years) with Median Rest Period (Simplified as 50% of ARP-UT)	21.6 (94%)	19.5 (94%)
Cracking Life (Years) with 10th Quantile Rest Period (Simplified as 12.5% of ARP-UT)	19.1 (83%)	18.0 (88%)
Cracking Life (Years) without Rest Period Effect	14.8 (64%)	15.8 (68%)

[a] HMA: hot mix asphalt

[b] AB: aggregate base; CL: clay with low plasticity index

As expected, cracking life is shorter for shorter rest periods. The difference between using the ARP-UT and the actual median rest period is about 6% (i.e., 100% minus 94%), which is believed to be minimal and can therefore be accounted for as part of the model calibration. The difference between using median and 10% quantile rest periods is about 10% (i.e., 94% minus 83%). This difference is currently addressed in *CalME* as part of the between-project variability. It is also possible to address this as part of the within-project variability by including traffic variability in the Monte Carlo simulations. The difference between using median rest period and assuming no rest period effect is about 30% (i.e., 94% minus 64%), which is believed to be too significant to ignore.

6 CONCLUSION

It is generally agreed that rest period between adjacent trucks can allow some degrees of recovery for flexible pavement from fatigue damage, which can have an important effect on pavement life. In this study, the characteristics of rest periods of highway truck traffic were investigated and their effects on pavement performance were evaluated using actual traffic data. Specifically, traffic data for February, May, August, and November of 2015 were extracted and analyzed for 40 operational WIM stations across California. After reviewing the distributions, different quantiles of the rest periods were calculated on an hourly basis for each WIM station. It was found that in general the rest periods are inversely proportional to the corresponding hourly truck traffic volumes, which is expected. The correlations were also found be independent of the WIM station locations and seasons of the year. Furthermore, the 0.5 quantiles (i.e., median) are proportional to but slightly shorter than the theoretical ARP-UT. Analysis of the same traffic data shows the existence of truck-following, which was believed to be the reason why the 0.5 quantiles are slightly shorter than the ARP-UT.

Given the similarity between actual rest periods and the ARP-UT, an evaluation of whether truck traffic could be simplified as uniform in pavement designs was conducted. An ME design program, *CalME*, was used to evaluate the difference in pavement performance caused by using the ARP-UT instead of the various quantiles of the rest periods. In addition, a third scenario was also evaluated where the rest period was set to zero and its effect turned off. The conclusion was that that the rest period effect cannot be ignored in *CalME*, but truck traffic can be safely assumed to be uniform to account for the effect of rest period.

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