Speed Effect Analysis and Canceling Model of a Response-Type Road Roughness Measuring System

JIAN LU, CARL BERTRAND, AND W. R. HUDSON

Response-type road roughness measuring (RTRRM) systems have been widely used in the United States and internationally in the evaluation of pavement surface roughness. One of the major problems associated with the calibration and operation of RTRRM systems has been the speed dependence of the systems. A reporting statistic from an RTRRM system has to be reported and qualified with speed of operation before the statistic has a meaningful relationship with surface roughness. Because the frequency pass band of an RTRRM system is limited, the outputs of the instruments are also affected by the frequencies of the surface profile. The Center for Transportation Research (CTR) of The University of Texas at Austin has been in the process of calibrating Highway Product International's Automatic Road Analyzer (ARAN) unit for the Texas State Department of Highways and Public Transportation (SDHPT). During the process, a statistical model was developed to cancel the speed effect from the ARAN output. The methodology for generating this model can be applied to any of the various types of RTRRM instruments.

The research effort concerning the model being conducted by CTR is introduced. The testing speed effect is analyzed by use of the transfer function of a simulation model of an RTRRM system [i.e., the reference quarter-car simulation (ROCS)]. The amplitude-frequency characteristics of the vehicle axle's vertical acceleration due to changing profile elevations are obtained. In order to quantitatively see the effect of the testing speed on the RTRRM system, it was necessary to simulate the ROCS by the digital difference equation approach with a sine function as the simulation input. A speed effect canceling model unit was generated, and also applied to the ARAN unit. The resulting model will be used to standardize the roughness outputs of the RTRRM system and eliminate the operational speed effect from the output statistics. The methodology is explained and can be applied to other types of RTRRM instruments.

The roughness of paved road surfaces has been explored and monitored by various highway agencies in the United States and throughout the world for many years. In the early 1960s, both static and dynamic instrumentation was being developed to monitor the pavement surface roughness. The surface roughness of paved roads has the following two main areas of concern for the highway design engineers and the riding public: (a) whether smoother road surfaces last longer than rougher roads, and (b) the user's perception of the roadway's ride quality.

Many different types of instrumentation have been developed over the years to monitor the surface roughness of the nation's roadways. These various types of instruments have been categorized broadly by whether they are static (manual) or dynamic in nature. Recently, the World Bank (J) has further classified these instruments according to their measurement intervals and the maximum error associated with their operation. FHWA has recently adopted this classification scheme (2) and has mandated its use to the individual states. The roughness monitoring instrumentation is divided into three categories:

Class I—Manually operated instruments, which accurately measure short-wavelength profiles of the roads. The measurement interval is less than or equal to 1 ft and the maximum error is 1.5 percent bias, or 19 in./mi. Examples of such instruments are the rod and level, the Face Dipstick, and the Transportation and Road Research Laboratory (TRRL) Beam.

Class II—Dynamic direct profiling instruments, which use a variety of methods to produce elevation data from the road surface. The measurement interval is less than or equal to 2 ft and the maximum error is 5 percent bias, or 44 in./mi. Examples of these instruments include the Longitudinal Profile Analyzer (APL) Trailer, GM profilometer, K. J. Law profilometer, and South Dakota profilometer.

Class III—Response-type road roughness measuring (RTRRM) systems that accumulate suspension deflections (axle to body or acceleration values) from the roadway surfaces. The maximum error associated with the operation of these instruments is 10 percent, or 32 to 63 in./mi, and the measurement interval is the test section length. Examples of these instruments include the Mays Ride Meter, Cox Roadmeter, Bureau of Public Roads (BPR) roughometer, and Automatic Road Analyzer (ARAN) unit.

The basic concept of Class I and II systems is the measurement of pavement surface profiles with limited wavelengths. Obviously, the shortest and the longest wavelengths these instruments can monitor are limited to the sampling interval of the system and the length of the body equipped with this kind of system. Class I instruments do not give information about how vehicles and their passengers will react or perceive the ride quality of the surface being monitored. Class II systems usually use filtering (hardware or software) to limit the influence of the longer wavelengths. They also use filtering or data averaging techniques to limit the short wavelengths and smooth the incoming elevation data. These two classifications give good indications of the true profile of the surfaces being monitored but may not relate to the user's perception of the surface profile.
The pavement surface ride quality can be directly related to the passenger's perception of the vehicle vibration, or the vehicle's response to certain frequencies. Class III instruments attempt to give an indication of the user's perception to the road's surface profile by monitoring the dynamic response of a mechanical device as it travels over the surface at a constant speed. These RTRRM systems use a variety of techniques, such as axle and body displacement transducers and accelerometers, to measure vehicle response. Class III instruments are the most widely used high-speed roughness monitoring devices in use today because they are relatively inexpensive, high-speed instruments that give good indications of the user's perception to the surface roughness. However, the RTRRM system outputs are speed dependent. That is, the reporting speed. These RTRRM systems use a variety of techniques, are the most widely used high-speed roughness monitoring instruments, to measure vehicle response. Class III instruments to the passenger's perception of the vehicle vibration, or the road's surface profile by monitoring the dynamic response of a mechanical device as it travels over the surface at a constant speed. These RTRRM systems use a variety of techniques, such as axle and body displacement transducers and accelerometers, to measure vehicle response. Class III instruments are the most widely used high-speed roughness monitoring devices in use today because they are relatively inexpensive, high-speed instruments that give good indications of the user's perception to the surface roughness. However, the RTRRM system outputs are speed dependent. That is, the reporting statistics will be different on the same road surface if the speed of travel is different. The different suspension system characteristics of each RTRRM vehicle make each response to a surface profile unique. These facts make it necessary to calibrate and standardize the outputs so that the reporting statistics from one vehicle can accurately be related to those of another vehicle.

To cancel the effect of speed dependence theoretically, two methods could be used, i.e., the system identification method and the statistical modeling method. The system identification method is carried out by conducting a series of dynamic tests on each RTRRM system. A set of parameters for each suspension system is estimated by means of these tests. The dynamic response characteristics of the suspension system can then be approximated by describing an abstracted dynamic response model in the time domain, or a transfer function in the frequency domain. Usually, these mathematical models need to be linearized and the corresponding dimensional degree should be as small as possible to simplify the model. Linearization of mathematical models also simplifies the solution to complex mathematical relationships. After the dynamic response model is identified, the speed dependence of the RTRRM system can be canceled mathematically. But, in practice, different vehicles have different dynamic response characteristics, and, therefore, the models should be different. Under normal circumstances, it is not worthwhile to test the dynamic parameters for each RTRRM system because the test procedure is complicated and expensive. Generally, it is not practical to use the system identification method to cancel the effect of speed dependence.

The basic concept of the statistical modeling method is to correlate the outputs of an RTRRM system collected from field tests, with their outputs at different testing speeds. The statistical relationships between the roughness outputs and the corresponding speeds can largely cancel the effect of speed dependence. The basic speed effect canceling model that results from the statistical method is relatively simple, and the methodology for the modeling can be used for practically all RTRRM system vehicles. The RTRRM systems must have relatively repeatable response for the same surface roughness characteristics before this approach is valid. But the coefficients in the speed effect canceling model should be estimated for each individual RTRRM system so that the corresponding speed effect canceling model can be generated.

The researchers have chosen the statistical method for modeling and canceling the RTRRM system speed effects because it is simpler and more practical than the dynamic response method. This paper describes how the speed effect canceling model was derived by the statistical modeling method. This model is applied to the ARAN unit and the result is a specific speed effect canceling model generated for the ARAN unit.

In order to explain how the testing speed affects the outputs of RTRRM systems, the reference quarter-car simulation [RQCS (3)] of an RTRRM system is introduced. The transfer function of the axle vertical acceleration to the pavement profile elevation is derived. Then, the amplitude frequency characteristics of the transfer function are used to explain the testing speed effect.

A quantitative simulating analysis is presented with an explanation of the testing speed effect using amplitude frequency characteristics of the transfer function of RQCS. The transfer function of RQCS is transformed into a digital difference equation corresponding to RQCS. The pavement profiles are then simulated by a sine function. The sine wave is input into the digital difference equation with different testing speeds. In this way, the simulated relationship between the output of RQCS and the testing speed is obtained.

The Center for Transportation Research (CTR) at The University of Texas at Austin has been evaluating and calibrating different subsystems of the Highway Product International (HPI) ARAN unit for the Texas State Department of Highways and Public Transportation (SDHPT). One of these subsystems involves the one that reports surface roughness statistics. During this evaluation and calibration effort, a mathematical model was developed for modeling the dynamic response of the suspension system. A statistical model has been generated for canceling the speed effect from the reported statistics.

**SPEED EFFECT ANALYSIS BY TRANSFER FUNCTION AND SIMULATING MODEL**

**Reference Quarter-Car Simulation**

The outputs obtained by an RTRRM system are based on the response of the vehicle to pavement surface profiles or slopes. Accurate modeling of the suspension system of the vehicle equipped with a measuring system is very complicated and expensive. RQCS, a simplified reference simulation of an RTRRM system, can be used in the analysis of the dynamic characteristics of an RTRRM system with certain boundary conditions. Figure 1 shows RQCS with the following parameters:

\[
K_1 = \frac{K_t}{M_t} = 653 \text{ sec}^{-2}
\]

\[
K_2 = \frac{K_i}{M_i} = 63.3 \text{ sec}^{-2}
\]

\[
U = \frac{M_s}{M_t} = 0.15
\]

\[
C = \frac{C_t}{M_t} = 6.00 \text{ sec}^{-1}
\]
The dynamic mathematical model shown in Figure 1 is defined mathematically by two second-order differential equations:

\[
\frac{d^2 Z_s}{dt^2} + C \left( \frac{dZ_s}{dt} - \frac{dZ_u}{dt} \right) + K_s (Z_s - Z_u) = 0
\]

(1)

and

\[
\frac{d^2 Z_u}{dt^2} + U \frac{d^2 Z_u}{dt^2} + K_s Z_u = K_i X
\]

(2)

where \(X, Z_s,\) and \(Z_u\) are defined as shown in Figure 1. Clearly, because Equations 1 and 2 are linear and constant equations, these two equations can be used only in a relatively narrow range because the linearization process is valid only within the given limits.

**Amplitude-Frequency Characteristic of RQCS**

Equations 1 and 2 describe the dynamic relationship of the displacements \((Z_s,\) and \(Z_u)\) and profile elevation \(X.\) Some RTRRM systems measure vehicle vertical acceleration instead of displacement. Therefore, to consider the amplitude-frequency characteristics with vehicle axle vertical acceleration as output, Equations 1 and 2 need to be changed using the following substitutions:

\[
a_s = \frac{d^2 Z_s}{dt^2}
\]

(3)

and

\[
a_u = \frac{d^2 Z_u}{dt^2}
\]

(4)

where \(a_s\) is the vehicle body vertical acceleration, and \(a_u\) is the vehicle axle vertical acceleration.

One of the best methods for frequency characteristics analysis is the Laplace transform method. By taking the Laplace transform of both sides of Equations 1, 2, 3, and 4, the following equations in the frequency domain can be obtained:

\[S^2 Z_s(S) + C S [Z_s(S) - Z_u(S)] + K_s [Z_s(S) - Z_u(S)] = 0\]

(5)

\[S^2 Z_u(S) + U S' Z_u(S) + K_i Z_u(S) = K_i X(S)\]

(6)

\[A_s(S) = S^2 Z_s(S)\]

(7)

\[A_u(S) = S^2 Z_u(S)\]

(8)

where \(S\) is the independent variable of the Laplace transform, and \(Z_s(S), Z_u(S), A_s(S), A_u(S),\) and \(X(S)\) are the Laplace transforms of \(Z_s, Z_u, a_s, a_u,\) and \(X,\) respectively. From these equations, the transfer function \(H(S)\) of axle vertical acceleration \(a_u\) to profile elevation \(X\) is expressed as

\[H(S) = \frac{A_u(S)}{X(S)}\]

\[= \frac{K_s S^4 + K_i C S^3 + K_s K_i S^2}{US' + (UC + C) S^3 + (UK_s + K_2 + K_1) S^2 + K_i C S + K_i K_2}\]

(9)

or

\[H(S) = \frac{A_1 S^4 + A_2 S^3 + A_3 S^2}{B_1 S^4 + B_2 S^3 + B_3 S^2 + B_4 S + B_5}\]

(10)

where

- \(H(S)\) is the transfer function,
- \(A_1 = K_i,\)
- \(A_2 = K_i C,\)
- \(A_3 = K_i K_2,\)
- \(B_1 = U,\)
- \(B_2 = UC + C,\)
- \(B_3 = UK_i + K_2 + K_1,\)
- \(B_4 = K_i C,\) and
- \(B_5 = K_i K_2.\)

The amplitude-frequency characteristics of RQCS (for which \(a_u\) is the output, \(X\) the input) are expressed by the following equation:

\[|H(\omega)| = \frac{|A_u(\omega)|}{|X(\omega)|} = \frac{(A_1 \omega^4 - A_2 \omega^3 + A_3 \omega^2 + A_4 \omega^1 + A_5 \omega^0)}{\sqrt{(B_1 \omega^4 - B_2 \omega^3 + B_3 \omega^2 + B_4 \omega^1 + B_5 \omega^0)^2}}\]

(11)

where

- \(\omega = -Sj\) is angular frequency (rad/sec), and
- \(j = \sqrt{-1}.\)

Figure 2 shows the relative amplitude-frequency characteristic with the maximum value of \(|H(\omega)| (\text{Max}[H(\omega)])\) as the reference value, and the independent variable is frequency \(f(\text{Hz})\) with the transformation \(f = \omega/2\pi.\) From Figure 2, it can be seen that RQCS behaves like a bandpass filter, and,
when the frequency reaches approximately 12 Hz, the RQCS has maximum sensitivity.

A comprehensive subjective ride research study on the relative importance of pavement profile frequency on ride comfort was conducted by the Michigan Department of Transportation (5). The results indicated that the roughness contained at frequencies ranging from 1.5 to 37 Hz at 50 mph correlated the strongest with the subjective ratings. Further, human body sensitivity to vertical vibration is at a maximum in the range of 5 to 6 Hz. This frequency band for human body sensitivity is, unfortunately, contained in the passband of RQCS. In other words, if an RTRRM system fits the RQCS well, the system will respond to the roughness that includes the frequencies to which passengers are sensitive.

SIMULATING ANALYSIS OF RQCS WITH PROFILE OF A SINE FUNCTION

If the wavelength $\lambda$ of a given pavement profile is fixed, then the changing of speed is equivalent to the changing of the frequency of the profiles. Roughness results from an RTRRM system are definitely affected by operational speed because the process is dynamic. How are these results affected by the factor of speed? As seen in Figure 2, if frequency $f$ is less than 12 Hz, the sensitivity (gain) of RQCS increases as $f$ increases. Suppose a pavement profile is described by a sine function:

$$X(K) = A \sin \frac{2\pi vKT}{\lambda}$$

where

- $A =$ constant,
- $\lambda =$ wavelength (ft),
- $v =$ speed (mph),
- $T =$ sampling interval (sec), and
- $K =$ sample sequence index ($K = 0, 1, 2, \ldots$).

It can be understood that the frequency of this function is

$$f = \frac{5.280v}{3600\lambda} \text{ (Hz)}$$

(13)

Therefore, if $\lambda$ is assumed to be 6.5 ft, as speed $v$ increases from 0 to 53 mph, the sensitivity (gain) of RQCS increases, i.e., the acceleration of the axle vertical vibration increases.

A simulating analysis can be conducted using the approximate difference equation solution of RQCS. As shown in Equation 10, RQCS can be described by a Laplace transfer function. In order to obtain the approximate difference equation solution of RQCS, the transfer function needs to be changed by a bilinear transformation (6),

$$S = \frac{2Z - 1}{TZ + 1}$$

(14)

where $Z$ is the $Z$ transform factor.

Consequently, the Laplace transfer function is changed into a $Z$ transform transfer function:

$$\frac{A_u(Z)}{X(Z)} = H(Z)$$

$$\frac{C_1 + C_2Z^{-1} + C_3Z^{-2} + C_4Z^{-3} + C_5Z^{-4}}{D_1 + D_2Z^{-1} + D_3Z^{-2} + D_4Z^{-3} + D_5Z^{-4}}$$

(15)

where

- $A_u(Z) =$ $Z$ transform of $A_u$,
- $X(Z) =$ $Z$ transform of $X$,
- $C_i =$ \text{(values)}
- $D_i =$ \text{(values)}
Further, Equation 15 can be changed into

\[ D_1 a_u(Z) + D_2 Z^{-1} a_u(Z) + D_3 Z^{-2} a_u(Z) 
+ D_4 Z^{-3} a_u(Z) + D_5 Z^{-4} a_u(Z) 
= C_1 X(Z) + C_2 Z^{-1} X(Z) + C_3 Z^{-2} X(Z) 
+ C_4 Z^{-3} X(Z) + C_5 Z^{-4} X(Z) \tag{16} \]

Taking the inverse Z transform of both sides of Equation 16 results in

\[ D_1 a_u(K) + D_2 a_u(K - 1) + D_3 a_u(K - 2) 
+ D_4 a_u(K - 3) + D_5 a_u(K - 4) 
= C_1 X(K) + C_2 X(K - 1) + C_3 X(K - 2) 
+ C_4 X(K - 3) + C_5 X(K - 4) \]

or

\[ a_u(K) = \frac{D_1}{D_2} a_u(K - 1) - \frac{D_3}{D_1} a_u(K - 2) 
- \frac{D_4}{D_1} a_u(K - 3) - \frac{D_5}{D_1} a_u(K - 4) 
+ \frac{C_2}{D_1} X(K) + \frac{C_3}{D_1} X(K - 1) 
+ \frac{C_4}{D_1} X(K - 2) + \frac{C_5}{D_1} X(K - 3) 
+ \frac{C_1}{D_1} X(K - 4) \tag{17} \]

Equation 17 is the approximate difference (digital) equation solution of RQCS; \( a_u(K) \) is the \( K \)th digital value of the axle vertical acceleration sequence and \( X(K) \) is the \( K \)th digital value of the pavement profile elevation sequence.

Suppose the profile elevation sequence \( X(K) \) is a sine function described in Equation 12, or

\[ X(K) = A \sin \frac{2\pi}{\lambda} v KT = A \sin \frac{2\pi}{\lambda} K \Delta X \tag{18} \]

where \( \Delta X \) is the sample interval in distance.

If the roughness index root-mean-square vertical acceleration (RMSVA) (7) is defined

\[ \text{RMSVA} = \sqrt{\frac{1}{N} \sum_{K=1}^{N} [a_u(K)]^2} \tag{19} \]

where \( N \) is the sample length, then the simulated results can be obtained by Equations 17, 18, and 19, with the following parameters, variable \( v \) (mph), and initial values:

\[ A = 1 \]
\[ \lambda = 6.5 \, \text{ft} \]
\[ \Delta X = 0.5 \, \text{ft} \]
\[ T = \frac{21,600}{63,360 \, \text{mph}} \quad \text{(sec), and} \]

Initial values = 0.

RMSVA should be a function of speed \( v \) determined by the profile elevation sequence \( X(K) \). From the amplitude-frequency characteristics of RQCS (Figure 2), it can be expected that as \( v \) increases from 0 to 50 mph, RMSVA should increase monotonically. Figure 3 shows the simulated results of relative RMSVA versus speed \( v \), where relative RMSVA is defined by

\[ \text{Relative RMSVA} = \frac{\text{RMSVA (at } v \text{)}}{\text{RMSVA (at 50 mph)}} \tag{20} \]

The simulated results indicate how the factor of speed affects the roughness index.

Figure 4 shows the curve of relative RMSVA versus speed \( v \), obtained from a research study on the evaluation of the ARAN unit conducted by CTR. The data were collected by

![Figure 3](image-url)
the ARAN unit from a test section named ATS12. The effect of speed on RMSVA can be seen to be similar to that simulated by RQCS.

**SPEED EFFECT CANCELING MODEL**

The statistical method is more practical for canceling speed effect of the roughness output as measured by an RTRRM system than the system identification method as has been previously stated. The basic idea of implementing the statistical method is to run RTRRM vehicles in the field and obtain the statistical relationship of the roughness output to the testing speed. The roughness output measured at a testing speed $V_t$ can then be referenced to the roughness output at a standard speed $V_s$.

The roughness output measured at a testing speed $V_t$ can be defined as $RO(V_t)$. For a given test section, $RO(V_t)$ is the following function of $V_t$:

$$RO(V_t) = f(V_t)$$

(21)

where $f(*)$ is a continuous function and $f(*)$ can be obtained by curve-fitting techniques. For example, to demonstrate the methodology, assume $f(*)$ is a second-order function. It should be recognized that this $f(*)$ can be defined in different forms depending on the instrument to be described. Then

$$f(V_t) = A + BV_t + CV_t^2$$

(22)

where $A$, $B$, and $C$ are the coefficients that must be estimated. To estimate these coefficients, a certain number of test sections are run at different speeds. For each test section, the coefficients $A$, $B$, and $C$, and the value of $RO(V_t)$ can then be obtained. The following matrix can be generated from the test section data:

<table>
<thead>
<tr>
<th>Test Section</th>
<th>$RO(V_s)$</th>
<th>$A$</th>
<th>$B$</th>
<th>$C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>2</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>3</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>$M$</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

where $M$ is the number of the test sections run by the RTRRM system during field tests, and $RO(V_s)$ is the standard roughness output for a given test section, because $V_s$ is defined as the standard testing speed. If it is assumed that the coefficients $A$, $B$, and $C$ can be related to $RO(V_s)$ by the linear regression method or the curve-fitting technique, then

$$A = G_a[RO(V_s)]$$

$$B = G_b[RO(V_s)]$$

$$C = G_c[RO(V_s)]$$

(23)

where $G_a[RO(V_s)]$, $G_b[RO(V_s)]$, and $G_c[RO(V_s)]$ are continuous functions of $RO(V_s)$. From Equation 22, the following equation can be obtained:

$$RO(V_t) = GA[RO(V_s)] + GB[RO(V_s)]V_t + GC[RO(V_s)]V_t^2$$

(24)

where $G(*,*)$ is a two-dimensional continuous function of $V_t$ and $RO(V_t)$. If $G(*,*)$ is reversible in terms of $V_s$, then

$$RO(V_s) = R[V_t, RO(V_t)]$$

(25)

where $R(*,*)$ is the inverse function of $G(*,*)$ in terms of $V_s$.

Equation 25 is the speed effect canceling model. That is, whatever the testing speed $V_t$ for a particular test section, the standard roughness output can be obtained through Equation 25. For example, if $G_a(*)$, $G_b(*)$, and $G_c(*)$ are the first-order functions, i.e.,

$$A = a_1 + a_2RO(V_s)$$

$$B = b_1 + b_2RO(V_s)$$

$$C = c_1 + c_2RO(V_s)$$

(26)

then Equation 24 is

$$RO(V_t) = a_1 + a_2RO(V_s) + [b_1 + b_2RO(V_s)]V_t + [c_1 + c_2RO(V_s)]V_t^2$$

$$= \frac{(a_1 + 1) + b_1V_t + c_1V_t^2}{(a_2 + b_2V_t + c_2V_t)}$$

(27)
or
\[
\text{RO}(V_i) = \frac{\text{RO}(V_i) - (a_1 + b_1 V_i + c_1 V_i^2)}{a_2 + b_2 V_i + c_2 V_i^2}
\]
(28)

The canceling model just described can also be completed by a family of curves. The procedure for canceling the speed effect can be completed by referring to the corresponding curves. An example for the development and use of this model is contained in the following section.

APPLICATION OF THE SPEED EFFECT CANCELING MODEL TO RMSVA OF THE ARAN UNIT

In order to obtain the canceling model for the ARAN unit, 30 typical test sections were chosen around the Austin area. This study was sponsored by the Texas State Department of Highways and Public Transportation (SDHPT). The surface roughness statistics, as measured by the ARAN unit on these sections is root-mean-square vertical acceleration (RMSVA). The curves of RMSVA versus \( V_i \), are shown in Figure 5. From these curves, Equation 21 has the following form:

\[
\text{RMSVA}(V_i) = A + B V_i + (V_i - 25)
\]
(29)

Table 1 was obtained by curve fitting, interpolation, and letting \( V_s = 50 \) mph. Figures 6 and 7 show the curves of coefficients \( A \) and \( B \), respectively, versus RMSVA(\( V_s \)). The data points on the figures can be fitted by the first-order functions. Equation 26 can be used for the curve fitting to obtain the coefficients \( A \) and \( B \). The coefficients \( a_1 \), \( a_2 \), \( b_1 \), and \( b_2 \) and the corresponding correlation coefficients are shown in Figures 6 and 7. By applying Equation 28 with \( C_1 = 0 \), \( C_2 = 0 \), the mathematical model for canceling the speed effect is

\[
\text{RMSVA}(V_i)
= \text{RMSVA}(V_i) - \left[ -36.758 + 1.403(V_i - 25) \right] \frac{0.44407 + 0.022237(V_i - 25)}{0}
\]
(30)

The measured RMSVA can be referred to the standard output RMSVA(\( V_s \)) through Equation 30 regardless of the operational speed \( V_i \). Figure 8 shows a family of curves for canceling speed effect for the Texas ARAN unit. These curves were obtained by using the following procedure.

From Equation 30, for a given RMSVA(\( V_s \)), RMSVA(\( V_i \)) is a function of \( V_i \). Therefore, a curve of RMSVA(\( V_i \)) versus \( V_i \) can be obtained. By changing RMSVA(\( V_i \)), another curve of RMSVA(\( V_i \)) versus \( V_i \) can be obtained, and so on.

It is easy to use Figure 8. For instance, if the ARAN unit measures roughness data at speed \( V_i \), the measured RMSVA(\( V_i \)) must be converted to the standard roughness output RMSVA(\( V_s \)) according to \( V_i \) and RMSVA(\( V_s \)). The corresponding RMSVA(\( V_s \)) curve can be found at the intersection of the \( V_i \) and RMSVA(\( V_s \)).

For example, if the ARAN unit is operated at 40 mph (\( V_i = 40 \) mph) and the obtained RMSVA at 40 mph is 400 milligavrits (mg), then by substituting RMSVA(\( V_i \)) and \( V_i \) into Equation 30, the resulting standard RMSVA at 50 mph [RMSVA(\( V_s \))] should be 533.3 mg. Figure 9 shows how to obtain RMSVA(\( V_i \)) using the family of curves presented in Figure 8. The resulting RMSVA(\( V_i \)) from Figure 9 is the same as that calculated using Equation 30.
### Table 1: Coefficients and RMSVA(Vs) for Each Test Section

<table>
<thead>
<tr>
<th>Section</th>
<th>RMSVA (Vs), Vs = 50 mph</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATS01</td>
<td>585.820</td>
<td>215.415</td>
<td>14.813</td>
</tr>
<tr>
<td>ATS03</td>
<td>424.729</td>
<td>164.904</td>
<td>10.393</td>
</tr>
<tr>
<td>ATS07</td>
<td>313.286</td>
<td>129.496</td>
<td>7.352</td>
</tr>
<tr>
<td>ATS08</td>
<td>286.207</td>
<td>108.022</td>
<td>7.127</td>
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**Figure 6** Coefficient A versus RMSVA(Vs) at Vs = 50 mph.

**Figure 7** Coefficient B versus RMSVA(Vs) at Vs = 50 mph.
CONCLUSION

The roughness output for a given roadway measured by an RTRRM system increases as testing speed increases as shown by the simulation analysis of RQCS. In fact, as the speed increases, the feeling of the passenger’s comfort to the ride becomes worse because the gain of the suspension systems transfer function increases.

The speed effect canceling methodology of the RTRRM system presented in this paper may be suitable for all types of RTRRM systems, but, in order to set up a model for a specific RTRRM system, a series of field tests should be run so that some adequate function of Equations 21 and 23 and corresponding coefficients can be obtained. As stated in this paper, the method of obtaining the speed effect canceling model is a statistical method. It is hard to totally cancel the effect of speed on the outputs of an RTRRM system, but statistically, the model presented in this paper does significantly cancel the effect of speed.

It should be mentioned here that there are some limitations for this kind of speed effect canceling model. In order to apply the methodology presented in this paper to other RTRRM
systems, relatively good repeatability of the output roughness statistics is required. In addition, the output of the instrument using this speed effect canceling model should include information regarding the operating speed. Further research will be conducted to check the accuracy of this model. This research will include collection of actual profile data to use as inputs to the model presented.

REFERENCES


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