

[Special Topic]

IMPACTS OF DESIGN AND MATERIAL QUALITY ON PAVEMENT RUTTING PROGRESSION

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Infrastructure deterioration is influenced by a multitude of factors including design and construction quality. This paper focuses on quantifying the impacts of such initial condition variables on life-cycle performance. Although in previous research an analysis framework for investigating such impacts was developed, quantitative results were inconclusive due to data and model limitations. In this study a rutting progression model that explicitly captures design and material quality variables is used whereby the effects of these variables on rut depth evolution over time are analyzed in quantitative terms. The results are in turn used to motivate future research in understanding significant temporal tradeoffs in infrastructure provision.

Key Words: *infrastructure provision, initial quality, design-build-operate-maintain, life-cycle performance*

1. INTRODUCTION AND MOTIVATION

Infrastructure provision consists of various stages including planning, design, construction, and maintenance. Due to the long-lived nature of infrastructure systems, their deterioration plays a critical role in the provision process. This deterioration is partly influenced by factors determined early on, namely during the design and construction stages, including design and material quality. This partly motivates the value of the increasingly common design-build-operate-maintain (DBOM) delivery process. This study focuses on quantifying the impacts of initial condition variables on performance over time. Without such quantification, the ability to make sound decisions based on total life-cycle cost is rendered infeasible.

Earlier research¹⁾ developed an integrated cost-and deterioration-based framework for analyzing the sensitivity of performance to initial conditions. However, the limited cost data and deterioration models used did not support arriving at firm quantitative conclusions. The cost-based approach consists of estimating a model of maintenance cost (as a proxy for long-term deterioration) versus design and construction cost (as a proxy for initial quality). Unfortunately, the available cost data had various limitations that cast doubt on the quantitative results.

The deterioration-based approach consists of using deterioration models as "laboratories" whereby long-term condition is predicted under various initial quality scenarios. The limitations of the deterioration-based quantitative results arrived at by Mishalani and Olayé¹⁾ relate to the bridge deck deterioration model used. The condition in this model²⁾ is defined by an ordinal scale that represents the combination of several distress measures by a discrete rating. The discrete nature of these ratings renders the interpretation of the corresponding condition predictions difficult when assessing their sensitivity to the variables of interest. In addition, such a representation does not allow for the examination of specific distress types which is much more meaningful in terms of understanding temporal behavior. The model was also limited in terms of the absence of any explicit design and material quality variables and, therefore, different deterioration rates (in the form of transition probabilities) were used to indirectly specify initial quality levels for the purpose of the analysis. Finally, deterioration after 50 years of service was presented while the nature of the evolution of deterioration over time was not explored.

To address the above limitations, this study utilizes a comprehensive rutting progression model that captures a detailed set of variables which explicitly characterize design and material quality. The influence of such variables on the evolution of pavement

rutting over time is examined in quantitative terms under certain loading and environmental conditions.

2. CONTRIBUTIONS

The contributions of this paper are fourfold. First, although in theory it is expected that design and material quality influence deterioration and while Mishalani and Olayé¹⁾ provided indications of such impacts, the direct quantification of the nature and extent of these impacts on disaggregate distress measures has not been addressed. This study quantifies these impacts on pavement rutting, one of two primary distress measures based upon which maintenance decisions making is made.

Second, This quantification is based on the explicit relationship between design and material quality on the one hand, and rut depth on the other. This is in contrast to the indirect approach Mishalani and Olayé¹⁾ resorted to due the limitations of the model they used as discussed in section 1. Therefore, the results arrived at in this study are more reliable due to the use of a rutting model that readily includes design and material quality explanatory variables.

Third, the analysis does not only focus on the separate impacts of design and material quality on rutting, but also investigates the interaction between design and material quality. This is essential in making optimal decisions on these variables simultaneously. This is particularly important given the specific nature of their interaction as discussed in subsection (3) of section 5.

Finally, The application of the rutting model in this study resulted in its critical review and consequent identification of important characteristics which point to directions of future research essential for both deterioration modeling and further assessing the impacts of design and material quality on performance.

The remainder of this paper is organized as follows. First, the employed rutting progression model is presented. The specification of the various scenarios is then discussed. The prediction results are subsequently analyzed. This is followed by a critical review of important characteristics of the employed rutting model. Finally, the paper concludes with a summary and remarks regarding future research.

3. PAVEMENT RUTTING MODEL

The two main distress types of interest in modeling pavement deterioration are cracking and deformation as captured by rutting. This paper focuses on the latter while the treatment of the former is reserved for

future research. Recently Archilla and Madanat^{3), 4)} developed and estimated a non-linear incremental rutting progression model using experimental data resulting from two accelerated road tests⁴⁾. This model is adopted in this analysis due to the rich set of incorporated explanatory variables, rigorous specification, and efficient parameter estimates. These characteristics render this model the most useful given the objectives of this study.

For the purpose of this paper, presenting the overall structure of the model suffices. For the detailed specification, see Archilla and Madanat⁴⁾. For a given pavement section the rutting progression model consists of the following:

$$RD_t = c + \sum_s (\Delta RD_s^U + \Delta RD_s^{AC}) + u + \varepsilon_t \quad (1a)$$

$$\Delta RD_s^U = a_s \exp(bN_s) \Delta N_s \quad (1b)$$

$$\Delta RD_s^{AC} = m_s \exp(b'N'_s) \Delta N'_s \quad (1c)$$

where s = time period index ($s = 1, 2, \dots, t$); RD_t = rut depth at the end of period t ; c = initial rut depth immediately after construction (i.e., RD_0); ΔRD_s^U = increment in rut depth during period s that originates in the underlying layers; ΔRD_s^{AC} = increment in rut depth during period s that originates in the asphalt concrete layer (i.e., the pavement surface layer); ΔN_s and $\Delta N'_s$ = loading during period s for rutting originating in the underlying layers and the asphalt concrete layer, respectively, defined based on the equivalent single axle loads concept; N_s and N'_s = cumulative loading up to the end of period s for rutting originating in the underlying layers and the asphalt concrete layer, respectively; a_s = function of pavement layer thicknesses and the freeze-thaw process; m_s = function of asphalt concrete mix characteristics (i.e., material quality), loading (namely N'_s), and high air temperatures; b and b' = negative model parameters; u = time invariant random disturbance with zero mean and constant variance reflecting unobserved heterogeneity across the pavement sections; and ε_t = error term with zero mean and constant variance reflecting measurement errors and unobserved explanatory variables.

As a matter of clarification, the loading variables differ between the asphalt concrete layer on the one hand and the underlying layers on the other due to the nature through which axle loads at the surface are transferred to the respective layers. Naturally, the effect of usage on rutting is captured through the various types of axle load applications which in turn determine the loading variables. For the specific application of the concept of equivalent single axle

loads in each case, see Archilla and Madanat ⁴⁾. The effect of design is captured through the pavement layer thickness variables which directly influence a_3 . The effect of material quality is captured by three asphalt concrete mix variables—namely gradation index, voids filled with asphalt, and in-place air voids—which determine m_3 . Finally, the above model was estimated using a two-week period time resolution as governed by the data sets used.

4. METHODOLOGY

(1) Framework

There are two categories of factors that influence the deterioration process. The time invariant ones are initially set and include design and material quality variables as determined during the design and construction stages of the provision process, while the time variant factors include usage in the form of traffic loading, environmental conditions such as temperature and precipitation, and maintenance actions.

This study focuses on the effects of the initial time invariant factors on rutting progression when maintenance actions are not taken. In the absence of maintenance the effects on deterioration remain unaltered and, therefore, the results reflect the pure degradation process. The incorporation of maintenance activities in the analysis of rutting progression is reserved for future research. For existing results relating to maintenance and bridge deck deterioration, see Mishalani and Olayé ¹⁾. As for the effects of the environment, due to current data limitations and in order to limit the scope of the analysis, only one set of environmental variables is assumed. In future extensions, a variety of other conditions can be explored.

Therefore, scenarios are defined on the basis of combinations of various sets of design, material quality, and traffic loading variables under a single set of environmental variables. For each scenario, the rutting progression model of equations (1a) through (1c) is used to predict the evolution of rut depth over a 50-year period. The effects of design and material quality variables are then analyzed via comparisons across the various predicted mean rut depths and percent changes in rut depth along with hypothesis testing in order to capture the uncertainty in the predictions. This analysis is presented in section 5.

(2) Scenario definition

Based on three sets of design variables, three sets of material quality variables and six sets of loading variables, a total of 54 scenarios are considered. What follows are the detailed specification of each

Table 1 Values of design variables

	Design Levels		
	Low	Medium	High
Surface (cm)	2.54	5.08	15.24
Base (cm)	5.08	10.16	30.48
Subbase (cm)	0.00	15.24	40.64

set of variables along with the assumed environmental conditions.

a) Design

The variables that reflect design are the thicknesses of the surface asphalt concrete, base, and subbase layers of the pavement. As shown in **Table 1**, three combinations, reflecting a wide range of possibilities from the AASHO Road Test ⁵⁾ data set utilized in estimating the rutting progression model, are used to specify the scenarios with respect to design. As discussed in section 3, these layer thicknesses are used in determining the values of a_3 for each of the scenarios.

The actual values in the table comprise the combination of the smallest thicknesses found in the AASHO Road Test ⁵⁾ data set in the case of the low design level, the combination of the middle range thicknesses in the case of the medium level, and primarily the largest thicknesses in the case of the high level.

b) Material quality

The asphalt concrete mix variables that reflect material quality are gradation index (GI), voids filled with asphalt (VFA), and in-place air voids (AV). As explained by Archilla and Madanat ⁴⁾, the higher the GI the more deformable the aggregate structure is. The VFA captures asphalt content which at high values and high air temperatures contributes to significant rutting. The AV captures the degree of compaction immediately after construction. A high AV value reflects poor compaction which leads to more rutting under traffic loading.

As shown in **Table 2**, three combinations, reflecting a range of values in the WesTrack ⁴⁾ data set utilized in estimating the rutting progression model, are used to specify the scenarios with respect to material

Table 2 Values of material quality variables

	Material Quality Levels		
	Low	Medium	High
GI (%)	3.5	2.3	1.1
VFA (%)	92.2	81.3	70.4
AV (%)	9.5	6.4	3.2

Table 3 Values of loading variables

	Loading Level		
	Low	Medium	High
ΔN_s (urban)	20,007	26,972	33,937
$\Delta N'_s$ (urban)	87,113	117,440	147,767
ΔN_s (rural)	3,724	9,012	14,300
$\Delta N'_s$ (rural)	9,652	23,355	37,059

quality. The actual values for each variable reflect the average along with the average plus and minus the standard deviation across eight representative WestTrack sections as selected in Archilla and Madanat⁴⁾.

c) Traffic loading

The inputs to computing the incremental loading variables ΔN_s and $\Delta N'_s$ in addition to the corresponding cumulative variables N_s and N'_s are Average Daily Traffic (ADT) measures along with the corresponding percentage of trucks (broken down by their axle configuration). United States statistics for the year 2000⁶⁾ are used to determine these inputs. More specifically, the values of ΔN_s and $\Delta N'_s$ were computed for urban and rural roadways based on the average ADT measures across the 50 states along with the average plus and minus one standard deviation, in addition to the average percentage of trucks using equations (6) and (7) in Archilla and Madanat⁴⁾. The values are shown in **Table 3** and comprise the loading levels used in composing the scenarios.

d) Environmental conditions

The environment affects the rutting progression process, as captured by the model used in this study, in two ways. The variable m_3 is partly governed by the material quality variable VFA capturing asphalt content. As already discussed, high values of VFA result in significant rutting when combined with a high air temperature. The other environmental effect is due to the freeze-thaw process which is captured by the variable a_s . Maximum and minimum temperatures were used by Archilla and Madanat^{3),4)} to construct a thawing index which directly affects the value of a_s reflecting the situation where thawing results in rutting progressing at a faster rate.

In this analysis, the same series of environmental variables over a two-year period used in the rutting progression model estimation is assumed by repeating its application contiguously over the entire 50-year prediction horizon. Of course, as mentioned above, the scenarios can be expanded in future studies to reflect a range of environmental conditions.

5. ANALYSIS OF RESULTS

(1) Introduction

The predicted rut depths using the progression model under the scenarios discussed above are analyzed in two ways. First, the effects of each of design and material quality over time are examined separately with the other variables left unchanged. The intent is to quantify rutting progression behavior as it is influenced by a single factor. Second, the sensitivity of rutting over time to various combinations of design and material quality levels is examined. The intent is to assess the interaction of the two factors as they impact rutting progression.

The quantitative effects of loading are not discussed in this paper due to a limitation in the rutting progression model which is discussed in more detail in section 6. As a result, the effects of design and material quality are explored under each loading level separately. For convenience in presentation, however, only the results corresponding to the high urban traffic variables are shown and discussed in detail. The corresponding results under the other loading levels, although exhibiting different magnitudes, are similar in nature to those discussed in this section.

(2) Single factor effects

Naturally, with higher design levels lower magnitudes of deterioration are expected. **Figure 1** shows the evolutions of the mean rut depth over time as predicted under the three design levels when the material quality is set at the medium level. First note that the rutting progression functions generally follow a concave trend as expected and discussed in Archilla and Madanat⁴⁾. In addition, the functions converge to an asymptote which is consistent with the mathematical specification of the model. In this particular case, the rate of increase in rut depth over time starts to diminish markedly short of one year. In the case of the high design level, at that point in time the rut depth almost converges to the value of 9.6 mm reached at year 50, while in the case of the low design level, rut depth continues to increase up the value of 14.2 mm reached at year 50.

Since the predictions are of the mean rut depth, it is important to also examine the uncertainty as captured by the two random components u and ϵ_t of the model. As an approximation, it is assumed that these two random variables follow the Normal probability density function with variances as estimated by Archilla and Madanat⁴⁾. The null hypothesis that the rut depths under the low and high design levels are equal is rejected at the 0.25 significance level starting at time 7.56 years onward based on the alternate hypothesis that the rut depths under the low design level

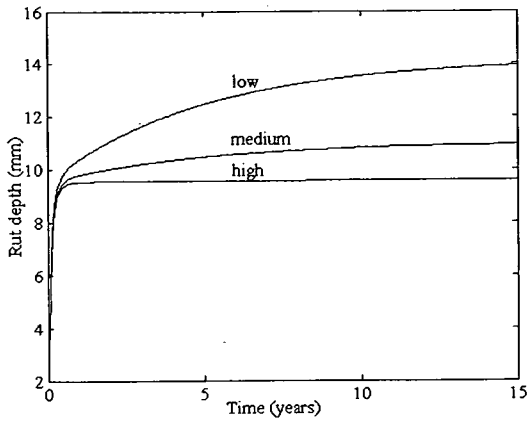


Figure 1 Effect of design

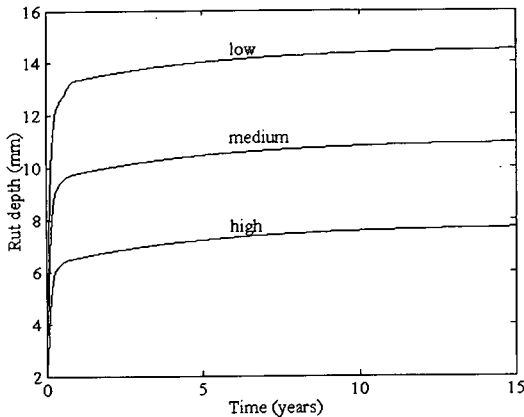


Figure 2 Effect of material quality

are greater than those under the high design level.

The effect of material quality is analyzed in a similar fashion. **Figure 2** shows the evolutions of the mean rut depth over time under the three material quality levels when the design is set at the medium level. Notice the similar patterns as those discussed above in terms of the rate of progression and convergence. In this case, however, the high material quality level results in the rut depth reaching 7.8 mm at year 50 while the low material quality level results in the rut depth reaching 14.6 mm at year 50.

In terms of the uncertainty in the prediction, the equality of the two rut depths under low and high material quality is rejected at the 0.25 significance level at time 0.077 years (almost one month) onward based on the alternate hypothesis that the rut depths under low material quality are greater than those under high material quality. For this set of scenarios, the null hypothesis can also be rejected at the 0.10 significance level at time 0.88 years (almost 10

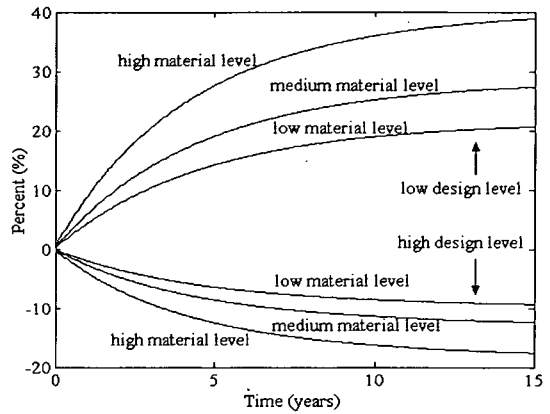


Figure 3 Sensitivity of rutting to both design and material quality

months) onward.

In both the case of design and material quality, it is clear that the variables governing these factors have significant impact on the rut depth progression. These results strongly indicate the potential value of determining design and material quality variables by considering life-cycle performance and cost.

(3) Joint factors effects

In addition to exploring the magnitudes of differences in rut depth under various scenarios as influenced by each factor separately, it is also useful to explore the sensitivity of rut depth as combinations of factors change. **Figure 3** shows the percent change in rut depth as it varies over time under high and low design levels measured with respect to the rut depth under the medium level. Results for all three material quality levels under high urban loading are shown. First, it is important to reemphasize that, as noted above, the magnitudes of these percent changes over the long-term, ranging in absolute value from approximately 10% to 40% depending on the scenario, clearly indicate that rutting progression is sensitive to design and material quality variables.

Second, notice that the magnitudes of the sensitivity of rutting to design levels depend on material quality. The sensitivity is greatest under the high material quality levels as reflected by approximately +40% and -18% at year 50 for low and high design levels, respectively. In absolute value terms, these percent changes drop to approximately +22% and -10% at year 50 under the low material quality levels, respectively. These joint effects imply that the sensitivity of rutting progression to design levels increases with higher material quality. That is, when a low material quality level is employed (due to, for example, poor construction practices), rutting will

progress at a faster rate reducing the range of impact design has on rutting progression. Similarly, when a high material quality level is employed, rutting progresses at a slower rate where the impact of design is further enhanced.

This suggests that it may very well be the case that to make the best use of higher design levels, higher material quality levels need to be employed as well. Of course, it is not possible to reach firm conclusions on the optimal combination of factors by simply examining the physical manifestations. What eventually matters in making such decisions are the economic manifestations as captured by total life-cycle cost. Nevertheless, this result suggests that the effects of joint factors may play an important role in life-cycle-based optimization that includes initial design and material quality decision variables.

6. RUTTING MODEL CRITICAL REVIEW

The above quantitative results reveal significant sensitivity of rutting to design and material quality variables. Recall, the limitations of the bridge deck deterioration model used in Mishalani and Olayé¹⁾ did not allow for the explicit investigation of such variables. Rather, an indirect assessment was conducted rendering the results valuable in primarily qualitative terms.

The rutting progression model used in this study, while providing the necessary richness in specification not available in the model employed in Mishalani and Olayé^{1),2)} has an important limitation of its own that is worth further discussion. The data used in estimating the model are based on the AASHO and WestTrack road tests³⁻⁵⁾ whereby loading is applied in an accelerated fashion over a fairly short span of time (for example, two years). As Archilla and Madanat pointed out^{3,4)}, these data do not allow for arriving at inferences relating to material aging which in-service facilities are clearly subjected to.

An example of this limitation is reflected in the effect of loading. As a result of the mathematical specification of the rutting progression model characterized by equations (1a) through (1c) where cumulative and incremental loadings are employed as explanatory variables, the predicted mean rut depth under a certain level of incremental loading is not guaranteed to be systematically greater than the predicted mean rut depth under a lower incremental loading, assuming all else equal. This can be seen by examining equations (1b) and (1c) where the negative parameters b and b' accompanied with increasing cumulative loading variables over time may result in the rut depth converging to a higher asymptote for a lower incremental loading case even if

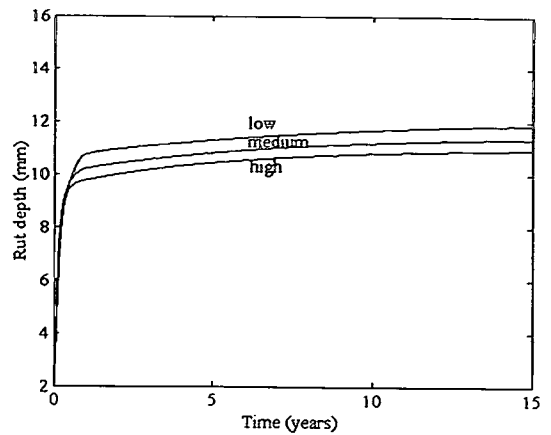


Figure 4 Rutting progression model limitation in the effect of loading

the corresponding earlier rates of progression are smaller.

This phenomenon can be observed in the mean rut depth predictions under medium design and material quality levels for high, medium, and low urban loading levels as seen in Figure 4. It is useful to point out that for the depicted scenarios the predicted rut depth under low loading exceeds that of high loading at time 0.41 years (almost five months) onward reflecting a manifestation of the limitation in question very early on in time.

Therefore, despite the value of the results discussed in section 5, long-term predictions of deterioration where aging is clearly a significant variable using models based on accelerated road tests should be interpreted with caution in terms of their representative qualities. Furthermore, the exploration of the effects of loading levels on long-term deterioration would not be useful. This is precisely why this analysis focused on the effects of design and material quality for each loading level separately.

7. SUMMARY AND FUTURE RESEARCH

This study was motivated by the qualitative findings of the previous research investigating the impact of initial conditions on long-term infrastructure performance. While the earlier study¹⁾ discussed the importance of such examinations and presented an analysis framework, quantitative conclusions were limited. The more detailed analysis conducted in this study lead to quantitative results confirming that each of design and material quality factors have significant impacts on rutting progression. Furthermore, the

nature of their joint effects is relevant to note as well. Specifically, the sensitivity of rutting progression to design levels increases with higher material quality levels.

Thus, the effects of design and material quality levels, whether separately or jointly, play an important role in life-cycle-based optimization. Naturally, the optimal balance between initial investments in design and material quality on the one hand and subsequent maintenance and rehabilitation activities on the other can only be assessed in the context of total life-cycle cost. The results presented in this paper further motivate the importance of investigating the value of incorporating initial design and material quality as decision variables within the life-cycle-based infrastructure management framework.

Another fruitful area worthy of further research is the continued refinement of deterioration models that are both rich in their specification such that the initial condition variables of interest are captured, and rich in the data sets drawn upon for their estimation such that long-term predictions are meaningful both in terms of the uncertainty involved and the necessity of reflecting the material aging process. This clearly points to the value of using field data reflecting in-service facilities and not solely rely on data produced from accelerated road tests. This is evident from the discussion in section 6.

Of course, research in this area should not be restricted to examining only rutting as a form of deterioration. The impacts of initial conditions on cracking, the other critical form of deterioration, is equally important to investigate and, hence, rich models capturing this type of failure are equally valuable.

Finally, given the importance of joint effects as exhibited in the discussion revolving around Figure 3 in subsection (3) of section 5, it is also important to extent this type of analysis to explore the effects of

other factors such as environmental conditions and routine maintenance as they interact with design and material quality.

With the advent of the DBOM infrastructure delivery process, the more critical it is to understand the complex relationships amongst all the variables that define or influence the performance of infrastructure systems. Without such understanding, the ability to make sound decisions based on total life-cycle cost is rendered infeasible.

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