Estimation of Pavement Damage Cost for Establishing Equitable Road Use Fee for Commercial Vehicles – An Exploratory Empirical Analysis

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ABSTRACT: Funding the maintenance, rehabilitation and reconstruction (MR&R) of highway infrastructure is becoming a challenging task for highway agencies around the globe. Highway agencies usually charge road use fees to the highway users that are either mileage based or proportional to the actual share of infrastructure damage occasioned. Current road user charges (highway toll) for commercial vehicles in Pakistan are based on expert opinion, thus completely disregarding equity impacts. Present study used a rational framework by incorporating the actual maintenance strategies used by national highway authority (NHA) of Pakistan for estimation of pavement damage cost. MR&R strategies (treatment type and timings) were formulated using twenty-five year life-cycle length and standard maintenance and rehabilitation treatments used by national highway agency. Marginal pavement damage cost (MPDC) for unit traffic loading was estimated by relating the highway agency pavement MR&R expenditure to the level of pavement loading. MPDC for national highway system was estimated to be Rs. 0.395 (2014 constant Rupees) per ESAL-km. Present study also compared the road use fee based on MPDC with existing road use fee for major truck classes and evaluated equity impacts.

INTRODUCTION AND LITERATURE REVIEW

In this era of growing travel demand and higher user expectation, overloading has become a common phenomenon and has led to rapid road infrastructure deterioration and premature failures. The accelerated pavement damage demands more frequent MR&R activities in order to meet road user expectations of enhanced serviceability. The highway agencies around the globe are striving to adopt efficient strategies for revenue generation so that MR&R treatments are not delayed unnecessarily.

Pakistan is a developing country that has a total road length of 260,000 kilometers (Km). NHA’s highway system which is only 4.6% of overall national road network carries approximately 80% of commercial traffic (PTPS, 2006). The latest figures show that the reliance on road transportation has increased from 8% to 96% in last few decades (ESP, 2012). In recent years damage due to overloading of heavy commercial vehicles has become a serious problem for local and national highway agencies in Pakistan. According to National Transport Research center (NTRC) load axle survey report, 83\%
loaded vehicles exceed the legal axle and gross vehicle weight (GVW) limit in Pakistan (Majeed, 1982). Past research has revealed that 70% of the two and three axle trucks and 40% of four, five and six axle trucks violate legal weight limits (MOI, 2007). The premature failure of highways, caused by overloading is responsible for increased demand for maintenance of highway infrastructure. Approximately 40% of the national road network was rated as poor or very poor condition in a national pavement condition survey of 2004 by Road Asset Management Division of NHA (PTPS, 2006). NHA’s Annual Maintenance Plan 2012 – 13, revealed that total toll revenue generated by highway agency using flat fee (fixed toll) for highway usage is insufficient to meet the increasing expenditures of road maintenance and rehabilitation (NHA, 2012).

This paper focused on estimation of MPDC using MR&R strategies practices by NHA of Pakistan. MPDC was estimated using MR&R strategies implemented by national highway agency and range of treatment service lives, and cost of pavement treatments obtained from past years. Further, this paper presents a comparison between current road use fee and actual pavement damage based on MPDC for different vehicle classes. This paper followed the generalized methodology developed by Ahmed et al. (2014).

In the past two approaches generally have been used for estimation of MPDC (1) Empirical approach and (2) Engineering approach. Martin (1994) conducted a study for Australian Road Research Board (ARRB) for estimating load-related pavement maintenance and construction costs. The author argued that heavy vehicles were responsible of 50 percent for highway maintenance and 45 percent for construction/replacement expenditures, respectively. Ghaeli et al. (2000) investigated the cost implications of different vehicle configurations and road characteristics based on the maintenance strategy used by Ontario Ministry of transportation. That study used the Ontario cost model to estimate pavement damage cost (PDC) in using equivalent single axle load – kilometer (ESAL-Km) as unit of pavement deterioration. Li and Sinha (2001) estimated the approximate load and non-load share of PDC for state of Indiana using ordinary least square (OLS) regression. PDC was estimated separately for flexible and rigid pavements. Herry and Sedlacek (2002) used OLS regression to develop a relationship between cost and traffic variables in order to estimate maintenance and rehabilitation marginal damage cost for Austria. Ozbay et al. (2007) estimate MPDC per different vehicle classes using pavement maintenance and rehabilitation data from New Jersey. Liu et al. (2009) estimated the PDC using the field data from Kansas Pavement Management Information System (PMIS). Ahmed et al. (2014) used data and practical repair strategies used by Indian Department of Transportation to estimate MPDC for state on Indiana.

A number of studies have used engineering approach for PDC estimation and are discussed herein. Newberry (1988) was the first to drive basic relationship between pavement deterioration and pavement expenditure to estimate MPDC. Vitaliano and Held (1990) used data from New York on different roadway segments to estimate MPDC. Lindberg (2002) estimated MPDC using data from Swedish long term pavement performance program for different highway types separately. Anani and Madanat (2010) estimated MPDC by considering both rehabilitation and maintenance expenditure for pavement treatments applied over an infinite analysis period.
RESEARCH METHODOLOGY

Following Ahmed et al. (2014) framework used for estimation of MPDC is shown in Figure 1. The detailed steps used for MPDC are discussed in the ensuing paragraphs.

The identification of standard pavement maintenance and rehabilitation (M&R) treatments used by highway agency is the first step for the estimation of MPDC. List of standard treatment was prepared using data from NHA of Pakistan. The treatments that are generally used by national highway agency included (1) functional overlay 30 mm thick, (2) functional overlay 50 mm thick, (3) functional overlay 50 mm thick with deep patching and cold milling, (4) structural overlay 100 and 120 mm thick, (5) structural overlay 120 mm thick with deep patching, (6) thin surface treatment, (7) crack sealing and (8) patching. The actual cost and traffic data were collected after the identification of M&R treatments. The cost data of rehabilitation, periodic and routine maintenance activities and reconstruction were obtained from NHA. The traffic data including the traffic volume (annual average daily traffic (AADT)), individual axle load and traffic growth factors were obtained from NHA Annual Maintenance Plan (2013). Truck AADT data were collected for a total of 709 sections and were categorized into six traffic groups: (1) very high traffic (AADT > 25,000), (2) high traffic (18,000 < AADT < 25,000), (3) medium traffic (12,000 < AADT < 18,000), (4) medium to light traffic (8,000 < AADT < 12,000), (5) light traffic (4,000 < AADT < 8,000), and (6) very light traffic (AADT < 4,000).

Highways are constructed to meet road user’s demand for longer periods of time. Therefore, the selection of appropriate length of pavement lifecycle (time between two consecutive reconstruction activities) was an important step for estimation of PDC. The pavement life cycle length of 25 years is used by NHA and same was used in present study. Information on M&R strategies used by highway agency is another important input for MPDC estimation. To formulate M&R strategies, pavement initial rest period (time from construction to first major rehabilitation) and treatment service life (time from treatment application to next treatment application of similar or higher intensity) data were obtained from past pavement projects and response to a questionnaire survey by a panel of 8 pavement experts.

Pavement’s life cycle cost includes the costs of rehabilitation, periodic and routine maintenance and reconstruction activities, excluding the construction cost. An MR&R profile is a set of rehabilitation and maintenance activities over one life cycle of a pavement (Ahmed A., 2012). The general pavement MR&R profile used in present study based on MR&R practises followed by NHA is shown in Figure 2. A total of thirty MR&R profiles were formulated based on the treatments types and their service lives using twenty five years life cycle length. Thus, five MR&R profiles were formulated for each level of traffic loading (very high, high, medium, medium to light, light and very light). The time span for each M&R treatment (functional or structural) was selected based on the range of their service lives.
The present worth of each MR&R profile over twenty five years life cycle was determined using a real discount rate of 5\% (Equation 1) as follows.

\[
P_{\text{PW}} = \sum_{i=1}^{r} \left[ \frac{\text{Cost}_i^{\text{Rehab}}}{(1+r)^{t_{\text{Rehab}_i}}} \right] + \sum_{p}^{p} \left[ \frac{\text{Cost}_i^{\text{PMT}}}{(1+r)^{t_{\text{PMT}_i}}} \right] + \sum_{x}^{x} \left[ \frac{\text{Cost}_i^{\text{RMT}}}{(1+r)^{t_{\text{RMT}_i}}} \right] 
\]  

(1)

Where: \( P_{\text{PW}} \) (M&R) = present worth of rehabilitation and maintenance treatment; \( r \) = real discount rate, \( n \) = the year of application of rehabilitation or maintenance treatment, \( r \) = the number of rehabilitation treatments applied to the pavement, \( p \) and \( x \) = the number of periodic and routine maintenance treatments applied to the pavement, Rehab = rehabilitation treatment, PMT = periodic maintenance treatment , RMT = routine maintenance treatment
The total life cycle cost was obtained by summing up the cost of different M&R activities over one pavement life cycle. The overall M&R cost and equivalent uniform annual cost (EUAC) of each M&R profile over twenty five years of pavement life cycle was estimated using (equation 2 and 3) as follows:

\[ MR&R \text{ Cost} = \text{Reconstruction Cost} + PW_{M&R} \]  
\[ EUAC(MR&R \text{ Cost}) = [MR&R \text{ Cost} \times \left( \frac{i(1+i)^n}{(1+i)^n-1} \right) ] \]

The average annual numbers of ESALs experienced by the pavement during twenty five years of life cycle were determined by suming up of annual ESALs for each truck class in each traffic group as follows.

\[ \sum_i ESAL = \text{Truck AADT} \times 365 \times D_d \times L_d \times G_f \times %\text{Class}_i \times ESAL \text{ Class}_i \]

Where, ESAL = Sum of Equivalent Single Axle Load of all truck classes for each traffic group, Truck AADT = Average Annual Daily Truck Traffic, Dd = Directional distribution factor, Ld = lane distribution factor, Gf = growth factor, %Class = percentage of trucks in traffic class i, ESAL class = individual ESAL of trucks in class i

MODEL DEVELOPMENT AND ESTIMATION OF MPDC

MR&R profiles formulated for each traffic group helped to generate thirty observations for model estimation. For the model estimation EUAC was considered as response variable and average annual ESALs as explanatory variable. OLS Regression techniques was used for the estimation of model. The functional form of best estimated model with R-square value of 0.77 is presented in (Equation 5) as follows:

\[ \sqrt{EUAC} = \beta_0 + \beta_1 \times (ESALs) \]
Where; $\beta_0, \beta_1 = \text{model coefficients}$, $\sqrt{\text{EUAC}} = \text{square root of equivalent uniform annual cost per lane-Km of the pavement over twenty five year analysis period}$, ESALs = average annual number of equivalent single axle load per lane Km. The model estimates are summarized in Table 1.

### Table 1. Model Estimates Results.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>t-Value</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>1457.157</td>
<td>145.054</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>ESALs</td>
<td>0.000147</td>
<td>9.686</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>R- Square</td>
<td></td>
<td>0.77</td>
<td></td>
</tr>
<tr>
<td>Number of observations</td>
<td>30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean Absolute Percentage Error</td>
<td>0.02</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The model results suggest that MR&R cost depends on traffic loading (ESALs), thus a pavement subjected to higher traffic loading shall have higher maintenance and rehabilitation cost, since pavement will need more frequent maintenance activities. The model accuracy is evaluated by estimating mean absolute percentage error (MAPE) as follows.

$$MAPE = \frac{1}{n} \sum_{i=1}^{n} |X_i|$$

Where, $X_i = (A_i - P_i)/A_i$ is the percentage error for an individual observation. The MAPE value for the above estimated model is 0.02. The MAPE value closer to zero depicts higher prediction accuracy of the model. MPDC was estimated by differentiating the estimated pavement damage cost function (equation 5) with respect to the ESALs as follows.

$$\frac{d(\text{EUAC})}{d(\text{ESAL})} = \frac{d}{d(\text{ESAL})} \left[\left[\beta_0 + \beta_1 \times (\text{ESALs})\right]^2\right]$$

$$\text{MPDC} = 2(\beta_1) \left[\beta_0 + \beta_1 \times (\text{ESALs})\right]$$

The MPDC for the year 2014 was estimated as Rs. 0.494 per ESAL-Km (2014 constant Pakistani Rs). The pavement deterioration is attributed to two factors: loading and climate. In order to separate the load share of pavement damage cost from non-load share an 80 – 20% split was considered. Load related MPDC was estimated as Rs. 0.395/ESAL-Km (2014 constant Pakistani Rs).

**COMPARISON BETWEEN CURRENT TOLL RATE AND ACTUAL PAVEMENT DAMAGE COST**

Comparison between road use fee based on MPDC and existing road use fee (fix flat fee) being charged to different vehicle classes was carried out by comparing two road fees for four different truck classes. For comparison purpose 275 km road segment of National Highway N-5 from Lahore to Islamabad was considered. Currently there are six toll plazas on N-5 and two/three axle trucks pay Rs 110 at each toll plaza while trucks exceeding three axles pay Rs 210 at each toll plaza. The current road use fee of six toll
plazas and road use fee based on MPDC for two, three, four, five and more than five axle trucks are presented in Table -2.

**Table 2. Comparison between Current Flat Road Use Fee and Road Use Fee Based on MPDC.**

<table>
<thead>
<tr>
<th>Truck Class</th>
<th>Current Toll Rate (Rs – 2014)</th>
<th>Road Use Charges based on MPDC (Rs – 2014)</th>
<th>Over/Under Payment of Road Use Fee</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two Axle</td>
<td>660</td>
<td>518</td>
<td>+21.5 %</td>
</tr>
<tr>
<td>Three Axle</td>
<td>660</td>
<td>1831</td>
<td>-177.4 %</td>
</tr>
<tr>
<td>Four Axle</td>
<td>1320</td>
<td>1884</td>
<td>-42.7 %</td>
</tr>
<tr>
<td>Five &amp; More Axle</td>
<td>1320</td>
<td>1478</td>
<td>-11.9 %</td>
</tr>
</tbody>
</table>

The study results revealed that the current road use fee (fix flat toll) being charged to commercial vehicles is inequitable as it fails to charge road users based on the actual damage incurred by each user class. Two axle trucks are overpaying approximately 21.50% of their fair road use fee, while three truck classes are underpaying their fair road use fee. Thus charging flat fee is resulting into equity issues. Also, once truckers are being charged a flat fee irrespective of their axle loading may result into overloading. Road use fee based on actual damage incurred by different vehicle classes will encourage the use of trucks with more number of axles thus reducing the overall pavement damage.

**SUMMARY AND CONCLUSIONS**

A thorough review of past studies at national level revealed that there has been lack of serious research efforts to estimate actual pavement damage cost for Pakistan. Present research effort used a realistic framework that incorporated the actual highway maintenance and rehabilitation practices used by national highway agency of Pakistan. MPDC was estimated using cost and traffic data obtained from NHA of Pakistan. MPDC was estimated to be Rs. 0.395 (2014 Constant Pakistani Rupees) per EASL-Km. The comparison of current road use fee (fix flat toll) and road use fee based on actual damage incurred by different vehicle classes revealed serious equity issues.

**REFERENCES**


