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Revisiting the Estimation of the Marginal Cost of Highway Maintenance

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Introduction

- Obtaining accurate estimates of highway costs caused by each class of vehicles is an important component of:
  - Evaluation of current user charges
  - Design of new pricing strategies

- Existing studies that estimate these costs have shortcomings.

Outline of presentation

- Background information
  - Engineering
  - Economics
- State-of-the-art in the estimation of marginal cost
- Methodology
- Results

Background – pavement deterioration

- Highway pavement deterioration is the loss of pavement performance.

- Pavement performance can be expressed in terms of:
  - Distresses (cracking, rutting, etc.)
  - Roughness
  - Serviceability (a combination of roughness and some distresses)

Cracking

Rutting

Roughness-measuring van

Photos: http://training.ce.washington.edu/WSDOT/

Background – pavement deterioration models

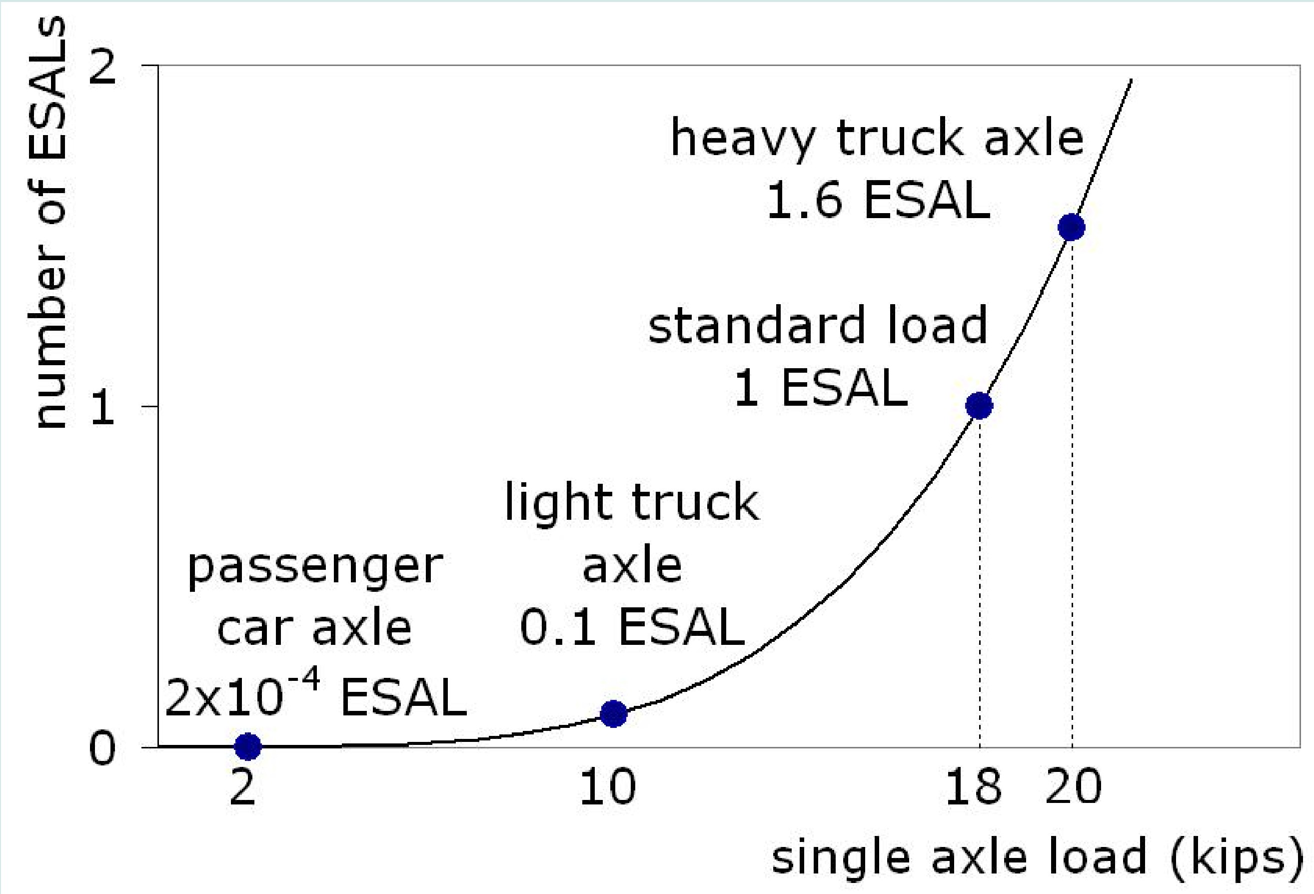
- A pavement deterioration model predict roughness, serviceability or a distress. Explanatory variables describe:

Traffic loading	Pavement structure	Current condition
Maintenance	Environment	Age

- Traffic loading is the total number of *deterioration equivalence factors* (DEF) passing during a time period. The number of DEFs for a vehicle expresses the relative pavement deterioration level that it causes.
- The axle loads of a vehicle determine its contribution to pavement deterioration. Number of DEFs per axle = $(\text{axle load/constant})^{\text{power}}$

Background – equivalent single axle load

- A commonly used DEF is the *equivalent single axle load* (ESAL), which assumes a power of four.
- For a single axle, ESAL = (axle load in kips/18 kips)^4



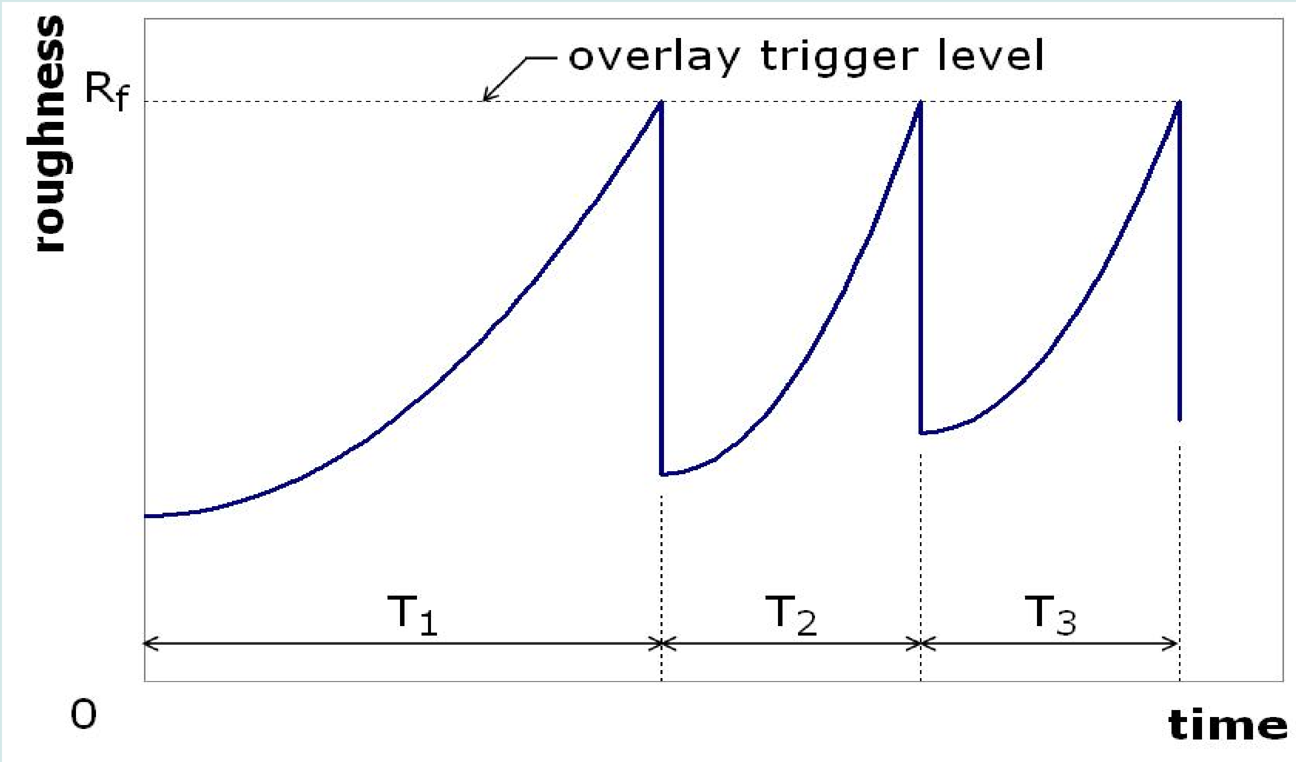
Background – pavement MR&R

- Pavement deterioration necessitates *maintenance, rehabilitation and reconstruction* (MR&R) activities.

Pothole repair

Photo: http://training.ce.washington.edu/WSDOT/

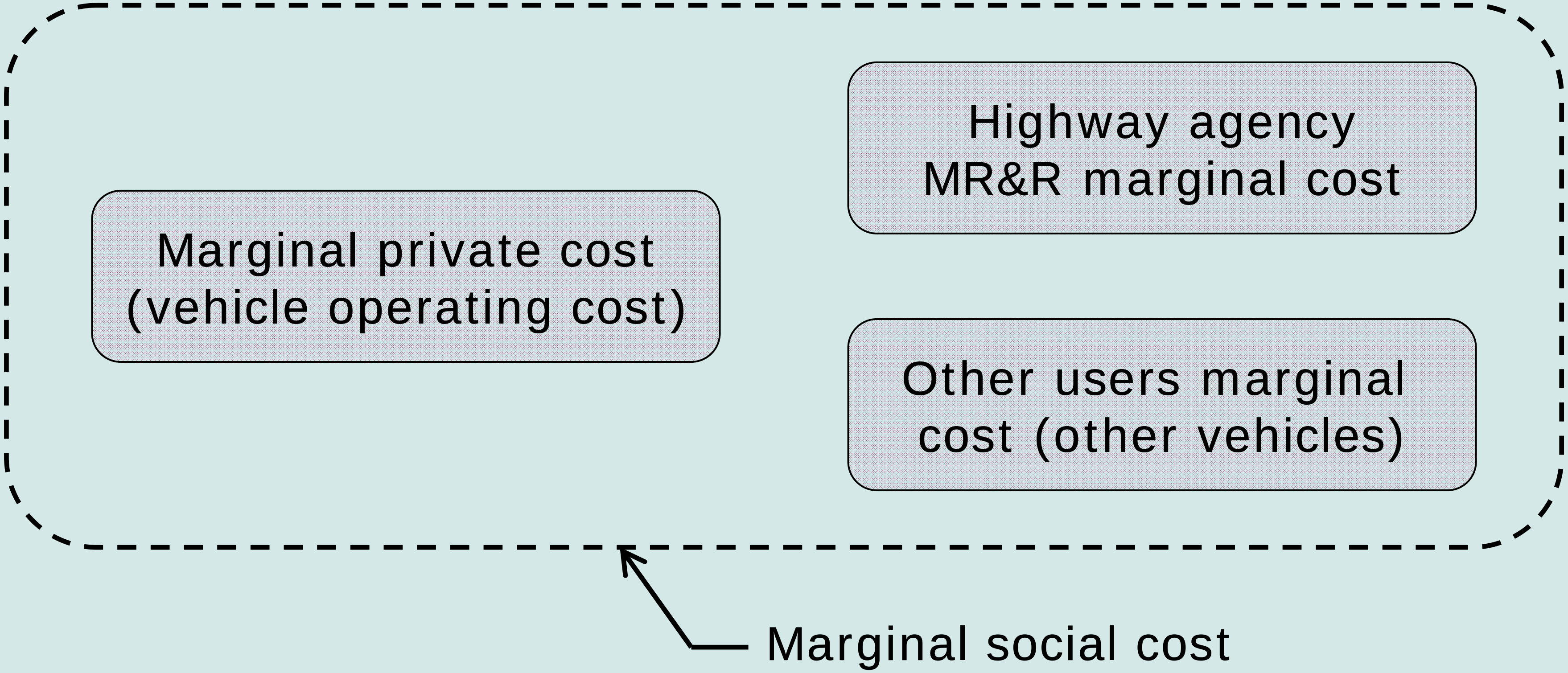
- MR&R strategies can be non-condition-responsive or condition-responsive.



A condition-responsive MR&R strategy

Background – marginal cost

- The cost caused to society by an additional unit of axle load
- Classification of highway pavement marginal costs:



Background – highway pricing

- *Marginal cost pricing* sets price equal to social marginal cost.

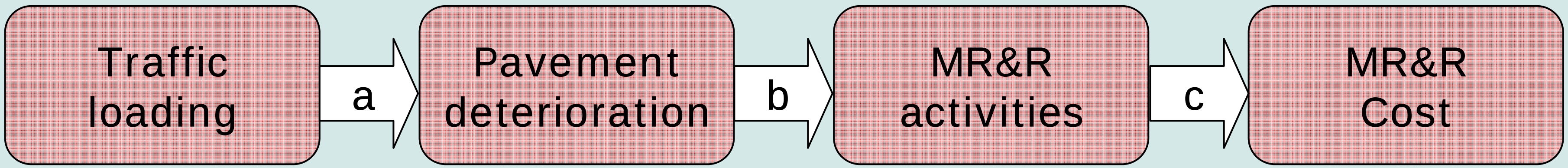
- Advantages of marginal cost pricing:
  - Economic efficiency
  - Equity

- Problems with highway pavement marginal cost pricing:
  - Difficulty in quantifying pavement marginal costs
  - Potential lack of cost recovery

Approaches for estimation of pavement marginal cost

- Approaches used in the literature[1]:
  1. The pavement management system direct approach
  2. The simple roughness approach
  3. The econometric approach
  4. The cost allocation approach
  5. **The perpetual overlay indirect approach (POIA)**

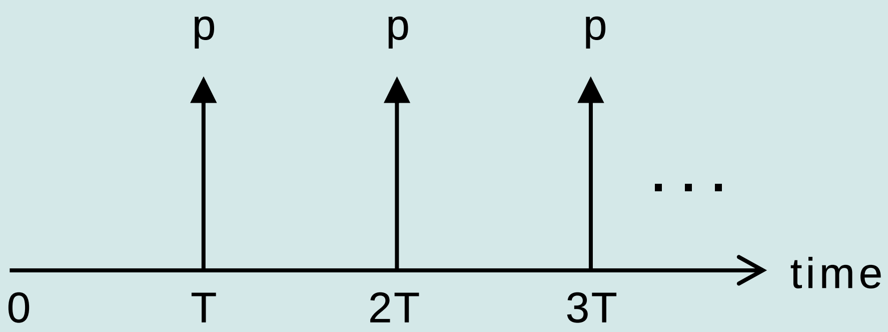
- In the POIA, marginal costs are estimated by linking MR&R activities to pavement deterioration, and thus to traffic loading:



1. Based on Bruzelius (2004)

The perpetual overlay indirect approach (POIA)

- Assumes a condition-responsive MR&R strategy that uses only overlays.
- Uses an infinite planning horizon.
- Uses ESAL as DEF. An additional ESAL is defined either as a *one-time event* or a *recurring annual event*.
- Assumes pavement deterioration and overlay effectiveness are deterministic.



Perpetual overlay costs

Common assumptions

- POIA studies make three unrealistic assumptions:

The first common assumption is that the increase in pavement deterioration is proportional to the fourth power of the axle load.

- The fourth power was obtained from the AASHO Road Test by defining deterioration as *loss in serviceability*. However, other definitions of deterioration are often used in practice.

Measuring axle load

Photo: FHWA website

Common assumptions

- The power used for DEF should depend on the type of deterioration, as the table shows:

Type of Deterioration	**Power used for DEF**	**Relevant study**
Loss of serviceability	4.15	Prozzi & Madanat (2004)
Increase in roughness	3.85	Prozzi & Madanat (2004)
Increase in rutting	**2.98** (for single axle) 3.89 (for tandem axle)	Archilla & Madanat (2000)

Common assumptions

The second common assumption is that the only MR&R activity used by a highway agency is an overlay of constant intensity.

- In reality, highway agencies often use strategies with multiple MR&R activities.
- Different MR&R activities are triggered by different indicators of pavement performance (cracking, rutting, roughness, etc.)

overlay

Photo: http://training.ce.washington.edu/WSDOT/

Common assumptions

The third common assumption is that pavement deterioration is deterministic.

- However, pavement deterioration is inherently stochastic. Thus, the time intervals between MR&R activities are random variables.
- Because the marginal cost is not a linear function of the time interval between MR&R activities, the expected marginal cost is not equal to the marginal cost estimated at the mean value of the time intervals.
- This third assumption is relaxed in this paper[2].

2. The authors are also working on relaxing the other two assumptions.

Methodology

- Assume highway agency uses a simple condition-responsive MR&R policy based on serviceability.

- Use stochastic duration model to predict deterioration, where the hazard rate follows a Weibull distribution.

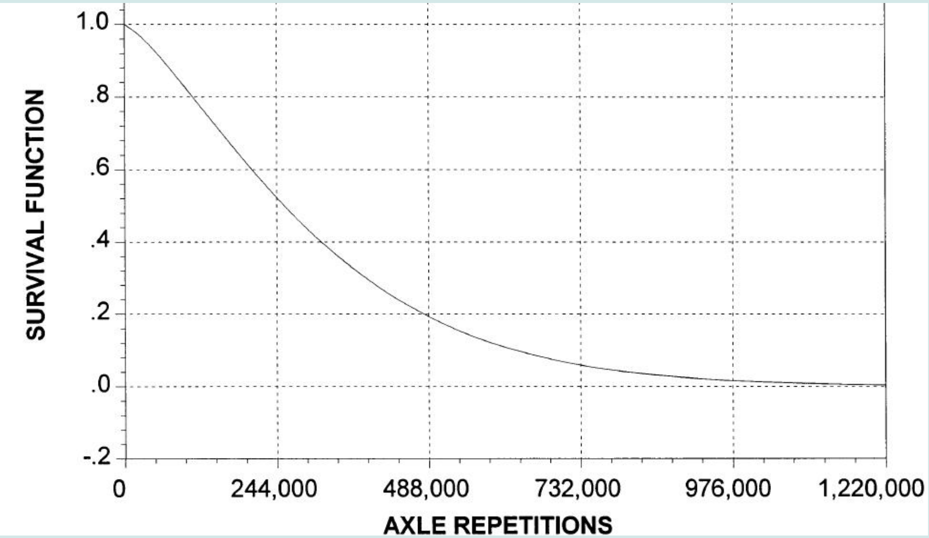
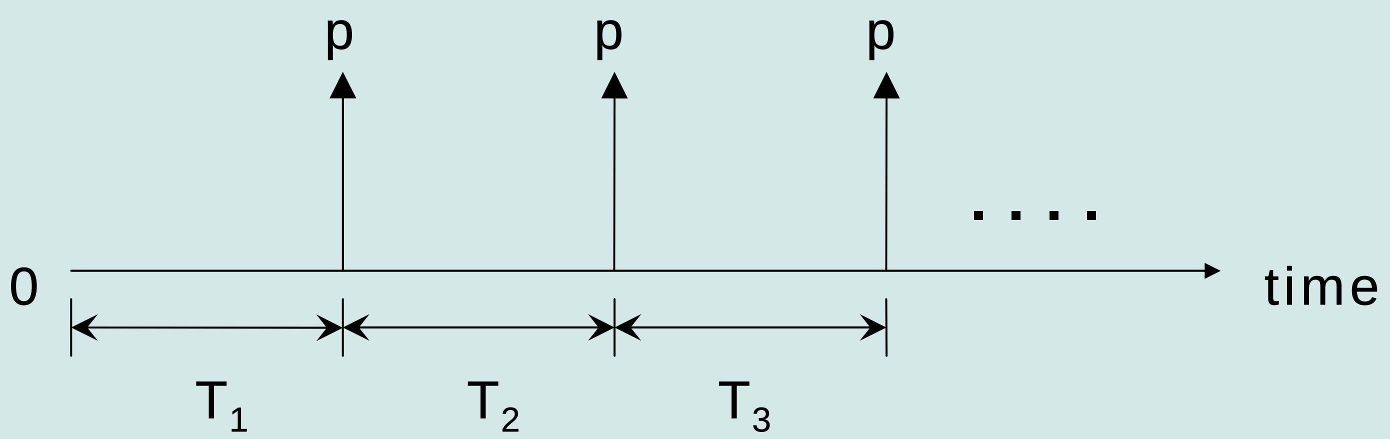


Figure from Prozzi & Madanat (2000)

- The number of ESALs to “failure” (trigger value) for the i^{th} overlay cycle is a random variable $\mathbf{X_i}$

Methodology

- Let positive constant **L** be the annual traffic loading (ESAL/year). Then, the duration of the i^{th} overlay cycle is defined as random variable $\mathbf{T_i}$ (year): $\mathbf{T_i = X_i / L}$



- Assume that $\{T_i\}_{i \geq 1}$ are independent, and identically distributed.

- Find expected MR&R marginal cost taken over the distributions of $\{T_i\}_{i \geq 1}$. Compare with deterministic case.

Results

- The results show that taking the stochastic nature of pavement deterioration into account increases marginal cost estimates by nearly 10% for typical pavements[3]:

Structural number	Annual traffic loading (ESAL/year)	Stochastic marginal cost ($/ESAL/mile)	Deterministic marginal cost ($/ESAL/mile)	Absolute percent difference[4]
2.1	10,000	2.2436	2.0426	9%
3.4	100,000	0.2161	0.1968	9%
5.2	1,000,000	0.0218	0.0199	9%
2.5	10,000	0.9871	0.8900	10%
3.9	100,000	0.1043	0.0943	10%
5.9	1,000,000	0.0106	0.0096	10%

3. Typical pavements are defined here as those designed to have expected overlay cycles of 5 years (in the first three computations) or 10 years (in the last three computations).

4. %|Difference| = $-(C'_{deterministic} - C'_{stochastic}) / C'_{stochastic} \times 100\%$

Results (continued)

- Both stochastic and deterministic marginal costs move in the opposite direction to the structural number and the discount rate, and in the same direction as the annual traffic loading, et ceteris paribus.

- The absolute percent difference (between marginal costs) moves in the opposite direction to the annual traffic loading, and in the same direction as the structural number and the discount rate, et ceteris paribus.

Conclusions

- The perpetual overlay indirect approach for estimating MR&R marginal cost makes three unrealistic assumptions.
- In this paper, we relaxed the third assumption. The results show that marginal costs estimated with stochastic pavement deterioration are nearly 10% higher for typical pavements.
- A pricing strategy based on the deterministic marginal cost would make the price paid by each vehicle fall short of the additional MR&R cost that it causes.