Designing Maintenance Policies

Philip A. Viton

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Quick Review (I)

We now understand:

- Road damage is caused by vehicle load (weight) distributed over vehicle’s axles.
- Damage is measured relative to 18,000 lbs weight on a single axle, the ESAL standard.
- We distinguish two types of roads: rigid (essentially a slab of concrete) and flexible (multi-layer, topped by bituminous concrete).
- We measure road condition by the Present Serviceability Index (PSI). Conceptually, two values are important:
  - $\pi_0 =$ value when road is new
  - $\pi_f =$ trigger value for when the road needs to be resurfaced
- The actual values depend on the type of road under consideration.
Road durability (D) is measured by inches of concrete (rigid roads) or Structural Number (flexible roads).

There is an empirically estimated equation relating the number of axle passages $N(D)$ to deteriorate a durability-$D$ road from $\pi_0$ to $\pi_f$.

We will usually prefer the version developed by Small and Winston rather than the original AASHO version, since it seems to give more plausible results.
This raises at least two questions:

1. If we are constructing or rehabbing roads, how durable should they be? What is the correct $D$ value?
2. In terms of maintenance policies, how often should we be doing road rehab?

As we will see, these are two sides of the same coin: if we know the answer to one, we will have the answer to the other.
We adopt the following framework for maintenance policies (typical in engineering practice).

- Regular maintenance: we will resurface the road every $T$ years.
- Re-surface the entire road (in the given direction) when the most-heavily-used lane needs it.

In this discussion we will ignore growth in traffic over time: this is relatively easy to incorporate, but for our purposes we will assume that ESALs today and ESALs next year are always the same.
Our assumptions imply the following picture of road condition over time:

![Diagram showing road condition over time with PSI on the y-axis and time on the x-axis, showing resurfacing at $T$, $2T$, and $3T$.]
Let’s now formalize this.

- Suppose our road has durability $D$.
- Then we can compute the number of ESALs, $N(D)$ that will cause the road to deteriorate from $\pi_o$ to $\pi_f$.
- Suppose traffic on the road generates $Q$ ESALs per year.
- Suppose that a proportion $\lambda$ of those ESALs are generated in the most-heavily used (outer) lane.
- Then annual ESALs in this lane — the only one that matters, by our assumptions — are $\lambda Q$

So the time period between the road needing resurfacing is:

$$T = \frac{N(D)}{\lambda Q} \text{ years}$$
It is important to see how $T$ (the resurfacing interval) and $D$ (road durability) fit together.

- From our equation for the period between resurfacings:

$$T = \frac{N(D)}{\lambda Q} \text{ years}$$

we see that once we have determined the desired durability $D$ of the road, then the maintenance schedule ($T$) falls out naturally.

- So all we really need to do is determine the desired road durability.

- Alternatively, if we could determine $T$ directly, then, given that we know the functional form for $N(D)$, we could solve for the correct $D$.

- It turns out to be easier to determine $D$, so that is what we will do.
We define an optimal $D$ as that durability that minimizes total public-sector costs. This is to ignore the impact of road roughness on users’ utility: we return to this later.

So we turn now to the costs associated with a choice of a durability level (ie of a particular maintenance policy).

- We ignore cost inflation over each maintenance cycle.
- Suppose it costs $k_m$ per lane-mile to resurface a road.
- Then, once we’ve chosen $D$, we incur costs as follows:
  - An up-front cost associated with initially building the road to durability $D$.
  - An infinite sequence of periodic resurfacing costs $k_m$, each $T$ years apart, where $T$ depends on our choice of $D$, as we’ve seen.
Then, introducing costs, our previous picture becomes
The important insight is that different choices of $D$ will result in different cost patterns over time.

- Low $D$: low up-front cost, but shorter $T$, so more applications of the maintenance cost $k_m$.
- High $D$: higher up-front cost, but longer $T$, so fewer applications of the maintenance cost $k_m$.

Note that for a given type of road, we expect the actual periodic resurfacing cost $k_m$ to be the same for each application: we’re restoring the road from the same $\pi_f$ to the same $\pi_0$ and we’re ignoring inflation: the only issue is how often we do it.

See the figures opposite. This is a typical trade-off problem: we are trying to balance the up-front cost against the periodic maintenance costs.
Low-$D$ maintenance policy

High-$D$ maintenance policy
Comparing Maintenance Policies

Our problem is that we need to compare possible policies ($D$’s) with:

- Different up-front costs.
- Different numbers of resurfacings.
- Different intervals between resurfacings.
Comparing Maintenance Policies

Our solution goes as follows:

- We replace each temporal pattern (stream) of costs with an equivalent single cost, incurred now.
- This is called the *Present Value* of the stream of costs.
- If we’ve done this correctly, then a decision-maker should be indifferent between
  - Incurring the actual stream of costs over time
  - Incurring (only) the present value now
- We can then compare different temporal patterns of costs by their present values.
- An *optimal* maintenance policy is the one with the lowest present value.
You’ve probably seen how to compute the present value of stream of costs incurred every period (year).

Our problem is different, for two reasons:

1. We want to be able to optimize our choice of $T$ (the maintenance interval), meaning that we need to consider continuous time.
2. Our costs are incurred only every $T$ years (rather than every year).

It turns out that the present value of a cost $C$ incurred every $T$ years in continuous time is

$$\frac{C}{e^{rT} - 1}$$

where $r$ is the discount rate. (The course website has a refresher on present value concepts).
Annualized Present Value of a Maintenance Policy

- Remember that maintenance occurs every $T$ years.
- As an alternative way of looking at the present value of a policy, we can take the present value and then expand it to (another) equivalent amount incurred every year (rather than every $T$ years).
- This is called the annualized present value or annualized cost.
- Using annualized cost can make it easier to compare costs and revenues, if revenues are received annually. (For optimization, annualization makes no difference).
- It turns out that for an infinite stream of costs $C$ incurred every $T$ years, the annualized cost is

$$\frac{rC}{e^{rT} - 1}$$

(the present value multiplied by $r$).
We also need to think about the up-front cost, which depends on our chosen $D$. We assume that for a $w$-lane road this up-front cost consists of:

- A fixed cost $k_0$ per mile.
- A cost $k_1 w$ that depends on the number of lanes to be resurfaced but not on their durability.
  - This is essentially the cost of grading the road surface (smoothing it out).
- A cost $k_2 wD$ that depends on the durability ($D$) of the road and on the number of lanes being built.
  - This is essentially the cost of the (volume of) materials needed to build or resurface the road.
The Up-Front Cost (II)

- So the up-front cost per mile for a \( w \)-lane stretch of road is
  \[
  k_0 + k_1 w + k_2 wD
  \]

- Since we focus on a 1-mile stretch of road, and we resurface the entire road when the outer lane needs it, we can simplify our problem by considering a 1-lane \( (w = 1) \), 1-mile road.

- This means that since we are deciding only on \( D \), the fixed cost and the cost depending only on \( w \) are irrelevant.

- We will integrate the durability and road width (choice of number of lanes) aspects of our problem later.

- So for now we take the relevant up-front cost per lane-mile to be just \( k_2 D \).
Putting these ideas together, the decision to build a durability-$D$ road results in annualized costs per lane-mile of

$$C^*(D) = \frac{r k_m}{e^{r N(D)/\lambda Q} - 1} + r k_2 D$$

where:

- $N(D) = A_0(D + 1)^{A_1} (L_1 + L_2)^{A_2} L_2^{A_3}$ (AASHO functional form)
- The $A$’s are estimated (say, with the Small-Winston values).
- $Q$ is annual ESALs generated on a mile of the road.
- $\lambda$ is an assumption about the proportion of the ESALs in the most-heavily-used lane.
- $k_m$ is the periodic maintenance cost per lane-mile.
- $k_2$ is the construction (up-front cost per lane-mile per unit $D$).
- $r$ is the discount rate.
The only unknown in the annualized cost equation

\[ C^*(D) = \frac{rk_m}{e^{rN(D)/\lambda Q} - 1} + rk_2 D \]

is \( D \), the road durability. (Remember that this differs as between rigid and flexible roads, because \( N(D) \) and the costs do).

Our task is to choose \( D \) to minimize this expression.

The result will be an optimal (ie cost-minimizing) durability, \( D^* \).

Once we have found \( D^* \) we can equivalently characterize our optimal maintenance policy by the optimal interval between resurfacings, \( T \), given by

\[ T = \frac{N(D^*)}{\lambda Q} \text{ years} \]

We solve the minimization problem numerically on a computer.
Data from Small-Winston-Evans (1989).

- This data is somewhat old (1982), but it is simple to adjust it for inflation.
  - There are a number of estimates of price inflation for road construction projects.
  - Roughly, between 1982 and late 2013, road construction costs rose by a factor of 2.64. (Source: Caltrans).
- Nonetheless, we will show results in \$1982.
Some Data (II)

- Periodic maintenance cost / lane-mile ($k_m$): ($)

<table>
<thead>
<tr>
<th>Type of Road</th>
<th>Urban</th>
<th>Rural</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interstate</td>
<td>169,267</td>
<td>75,539</td>
</tr>
<tr>
<td>Other freeway</td>
<td>169,267</td>
<td>54,102</td>
</tr>
<tr>
<td>Arterial</td>
<td>131,961</td>
<td>42,783</td>
</tr>
<tr>
<td>Collector</td>
<td>131,961</td>
<td>16,332</td>
</tr>
<tr>
<td>Local</td>
<td>131,961</td>
<td>18,374</td>
</tr>
</tbody>
</table>

- Fixed cost per lane-mile per unit $D (k_2)$; ($): 

<table>
<thead>
<tr>
<th>Type of Road</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Rigid Road</td>
<td>21,836</td>
</tr>
<tr>
<td>Flexible Road</td>
<td>11,718</td>
</tr>
</tbody>
</table>
Some Data (III)

We also take (with Small + Winston):

- $r = 0.06$ (may be too high for 2013)
- $\lambda = 0.7$ (6+lanes); $\lambda = 0.9$ (4–5 lanes); $\lambda = 1.0$ (1–3 lanes)
Some Results for Durability (D)

<table>
<thead>
<tr>
<th>Location</th>
<th>Type</th>
<th>Rigid Road (inches)</th>
<th>Flexible Road (SN)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Current</td>
<td>Optimal</td>
<td>Current</td>
</tr>
<tr>
<td>Urban</td>
<td>Interstate</td>
<td>10.07</td>
<td>13.52</td>
</tr>
<tr>
<td></td>
<td>Freeway</td>
<td>9.21</td>
<td>11.81</td>
</tr>
<tr>
<td></td>
<td>Arterial</td>
<td>6.78</td>
<td>7.50</td>
</tr>
<tr>
<td></td>
<td>Collector</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Rural</td>
<td>Interstate</td>
<td>9.52</td>
<td>11.35</td>
</tr>
<tr>
<td></td>
<td>Freeway</td>
<td>7.79</td>
<td>8.67</td>
</tr>
<tr>
<td></td>
<td>Arterial</td>
<td>6.52</td>
<td>6.59</td>
</tr>
<tr>
<td></td>
<td>Collector</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Local</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>
We have seen how to develop a correct (cost-minimizing) maintenance policy (ie how to select $D$).

What about paying for the roads?

We shall adopt the view that truckers ought to be charged for the damage that they do to a road.

Note that for now we are ignoring the congestion externalities generated by truck traffic.

We focus only on the marginal damage done to the road surface itself.
Durability Tolls — Theory

- How much damage does a vehicle do when it traverses a length of road?
- We know how to compute the total cost \( C^*(D) \) of a maintenance policy, for given \( D \) (and \( Q, \lambda, k_2, \) and \( k_m \))
- The value of the damage done by an additional ESAL is

\[
MMC = \frac{\partial C^*}{\partial Q}
\]

- This is the Marginal Maintenance Cost (per mile) of a road. It is a measure of the dollar value of the damage done by an additional ESAL on the road.
- If we charge a trucker this amount per ESAL-mile, we are in effect setting up a system of durability tolls.
Durability Tolls — Some Estimates

For the results previously described we have (in cents per esal-mile):

<table>
<thead>
<tr>
<th>Location</th>
<th>Type</th>
<th>Current D</th>
<th>Optimal D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban</td>
<td>Interstate</td>
<td>2.38</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>Freeway</td>
<td>4.32</td>
<td>0.61</td>
</tr>
<tr>
<td></td>
<td>Arterial</td>
<td>33.92</td>
<td>3.23</td>
</tr>
<tr>
<td></td>
<td>Collector</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Rural</td>
<td>Interstate</td>
<td>1.48</td>
<td>0.46</td>
</tr>
<tr>
<td></td>
<td>Freeway</td>
<td>4.38</td>
<td>1.13</td>
</tr>
<tr>
<td></td>
<td>Arterial</td>
<td>10.02</td>
<td>2.60</td>
</tr>
<tr>
<td></td>
<td>Collector</td>
<td>125.45</td>
<td>13.66</td>
</tr>
<tr>
<td></td>
<td>Local</td>
<td>40.92</td>
<td>40.92</td>
</tr>
</tbody>
</table>

These results are averaged over road types and volume ranges.
Optimal Durability Tolls

In the previous slide, note that the “current” durability toll is what it should be, given current durability levels: it is not to say that these tolls are actually charged.

- Do these results imply that we ought to be collecting these amounts from truckers at weigh-stations?
- Not necessarily, for two reasons:
  1. Truckers already pay taxes on their operations.
  2. When we get to the level of an individual truck operator, we ought to take into account the truck type and its weight.
Vehicle Types

- SU2  Single unit–two-axle
- SU3  Single unit–three-axle
- TT4  Truck trailer–four-axle
- TT5  Truck trailer–five-axle
- CS3  Conventional semi–three-axle
- CS4  Conventional semi–four-axle
- CS5  Conventional semi–five-axle
- CS6  Conventional semi–six-axle
- DS5  Double–five-axle
- DS6  Double–six-axle
Consider a truck loaded to 55,000 lbs GVW on urban roads. Then:

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Current Taxes</th>
<th>MMC with Current D.</th>
<th>Diff.</th>
<th>MMC with Optimal D</th>
<th>Diff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>SU2</td>
<td>4.22</td>
<td>183.38</td>
<td>179.16</td>
<td>71.89</td>
<td>67.67</td>
</tr>
<tr>
<td>SU3</td>
<td>5.61</td>
<td>41.43</td>
<td>35.82</td>
<td>16.24</td>
<td>10.63</td>
</tr>
<tr>
<td>TT4</td>
<td>5.08</td>
<td>23.67</td>
<td>18.59</td>
<td>9.28</td>
<td>4.20</td>
</tr>
<tr>
<td>TT5</td>
<td>5.94</td>
<td>9.18</td>
<td>3.24</td>
<td>3.60</td>
<td>−2.34</td>
</tr>
<tr>
<td>CS3</td>
<td>4.95</td>
<td>47.54</td>
<td>42.59</td>
<td>18.63</td>
<td>13.68</td>
</tr>
<tr>
<td>CS4</td>
<td>5.31</td>
<td>22.61</td>
<td>17.30</td>
<td>8.86</td>
<td>3.55</td>
</tr>
<tr>
<td>CS5</td>
<td>5.34</td>
<td>9.22</td>
<td>3.88</td>
<td>3.61</td>
<td>−1.73</td>
</tr>
<tr>
<td>CS6</td>
<td>5.36</td>
<td>5.45</td>
<td>0.09</td>
<td>2.14</td>
<td>−3.22</td>
</tr>
<tr>
<td>DS5</td>
<td>6.01</td>
<td>10.04</td>
<td>4.03</td>
<td>3.93</td>
<td>−2.08</td>
</tr>
<tr>
<td>DS6</td>
<td>6.06</td>
<td>6.22</td>
<td>0.16</td>
<td>2.44</td>
<td>−3.62</td>
</tr>
</tbody>
</table>

All values in cents per mile. MMC = marginal maintenance cost.
Same 55,000 lbs GVW vehicle, on intercity roads.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>SU2</td>
<td>2.91</td>
<td>64.26</td>
<td>61.35</td>
<td>13.74</td>
<td>10.83</td>
</tr>
<tr>
<td>SU3</td>
<td>4.23</td>
<td>14.52</td>
<td>10.29</td>
<td>3.10</td>
<td>−1.13</td>
</tr>
<tr>
<td>TT4</td>
<td>3.57</td>
<td>8.29</td>
<td>4.72</td>
<td>1.77</td>
<td>−1.80</td>
</tr>
<tr>
<td>TT5</td>
<td>4.41</td>
<td>3.22</td>
<td>−1.19</td>
<td>0.69</td>
<td>−3.72</td>
</tr>
<tr>
<td>CS3</td>
<td>3.49</td>
<td>16.66</td>
<td>13.17</td>
<td>3.56</td>
<td>0.07</td>
</tr>
<tr>
<td>CS4</td>
<td>3.84</td>
<td>7.92</td>
<td>4.08</td>
<td>1.69</td>
<td>−2.15</td>
</tr>
<tr>
<td>CS5</td>
<td>3.86</td>
<td>3.23</td>
<td>−0.63</td>
<td>0.69</td>
<td>−3.17</td>
</tr>
<tr>
<td>CS6</td>
<td>3.86</td>
<td>1.91</td>
<td>−1.95</td>
<td>0.41</td>
<td>−3.45</td>
</tr>
<tr>
<td>DS5</td>
<td>4.44</td>
<td>3.52</td>
<td>−0.92</td>
<td>0.75</td>
<td>−3.69</td>
</tr>
<tr>
<td>DS6</td>
<td>4.46</td>
<td>2.18</td>
<td>−2.28</td>
<td>0.47</td>
<td>−3.99</td>
</tr>
</tbody>
</table>

All values in cents per mile. MMC = marginal maintenance cost.
In the ‘Diff’ columns we show the difference between current taxes and the durability tolls implied by current and optimal maintenance practices.

Positive entries say that truckers are paying too little relative to a practice.

Negative entries say that they are over-paying.

Note that the number of positive and negative entries is about the same for current practice, but negative entries (over-payments) predominate, for optimal practice.

So at least for this truck weight, truckers would welcome a switch to an optimal maintenance (and toll) policy.
What if we implemented both optimal investment and the associated optimal durability tolls?

If we began charging MMC tolls, this would alter truckers’ incentives. They would have incentives to purchase trucks with more axles; and this would affect the ESALs generated on a road, hence optimal maintenance, and also toll levels.

To deal with this, Small, Winston and Evans (SWE) estimate a truck-choice (discrete-choice logit) model. That is, they model the determinants of truckers’ vehicle choices and how they would change if costs (tolls) changed.

Their results are equilibrium steady-state results, when things settle down (ie when the vehicle fleet composition isn’t changing over time).
In the table below, the optimal level is a steady-state equilibrium with respect to truckers’ decisions.

<table>
<thead>
<tr>
<th>Item</th>
<th>Current level</th>
<th>Optimal level</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pavement Costs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maint (excl disruption)</td>
<td>10.484</td>
<td>2.311</td>
<td>−8.173</td>
</tr>
<tr>
<td>Capital</td>
<td>9.636</td>
<td>10.913</td>
<td>1.227</td>
</tr>
<tr>
<td>Total</td>
<td>20.120</td>
<td>13.224</td>
<td>−6.896</td>
</tr>
<tr>
<td>Pavement Revenues</td>
<td>3.955</td>
<td>3.381</td>
<td>−0.574</td>
</tr>
<tr>
<td>Pavement Deficit</td>
<td>16.165</td>
<td>9.843</td>
<td>−6.322</td>
</tr>
<tr>
<td>Cost-Recovery Ratio</td>
<td>0.197</td>
<td>0.256</td>
<td></td>
</tr>
</tbody>
</table>
The bottom line is that resurfacing roads to an optimal durability would reduce roadway costs by $6.9m per year (remember, these are annualized costs).

Substituting durability tolls for current taxes would decrease revenues by 0.6m annually.

The net impact would be to reduce the pavement deficit (ie the need for funding roads from general revenues) by $6.3m annually.
To fully assess the impact of an optimal investment and pricing policy we need:

- An estimate of the value (willingness-to-pay, wtp) to freight shippers and carriers for the new policies
- Estimates of how the freight modal mix (eg trucks vs rail or air) changes as highway policies change.

SWE estimate these based on estimated demand functions for freight shipments: they then compute wtp as the area under these demand functions, in much the same way that we did in our discussion of optimal capacity/congestion.
Steady-state result (policies have been in effect for many years).

<table>
<thead>
<tr>
<th>Item</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Investment Costs</strong></td>
<td></td>
</tr>
<tr>
<td>Maintenance savings</td>
<td>$9.902</td>
</tr>
<tr>
<td>Capital cost savings</td>
<td>$-1.277</td>
</tr>
<tr>
<td>Total savings</td>
<td>$8.625</td>
</tr>
<tr>
<td><strong>Shippers’ and carriers welfare</strong></td>
<td>$0.134</td>
</tr>
<tr>
<td>Change in tax revenues</td>
<td>$-0.574</td>
</tr>
<tr>
<td>Impact of modal shifting (truck and rail)</td>
<td>$0.040</td>
</tr>
<tr>
<td><strong>TOTAL IMPACT</strong></td>
<td>$8.225</td>
</tr>
</tbody>
</table>

Change is $b/year relative to current practice. Maintenance savings includes an estimated $1.25m in disruption savings to motorists.
Bottom line: allowing for everything to settle down, a policy that combined optimal maintenance with durability tolls (instead of current truck taxes) could result in annual savings of $8.2b over current practice.

Most of this is savings on the highway side — the impact on shippers’ and carriers’ welfare is rather small.
Could this work, as a practical matter?

- The optimal investment component results in significantly more up-front spending on highways (a negative capital cost savings, because roads are now built as inefficiently durable).
- The maintenance cost savings would be less visible — recall that the costs we are dealing with are annualized, while actual maintenance expenditures are not (they occur every $T$ years).
- The optimal pricing component can result in price (charge) increases for at least some truckers; they would certainly oppose this.
Yes, but ... (II)

So let's ask: what if we implemented one component of this policy, but not the other.

Result (change from current policy, in $b per year):

<table>
<thead>
<tr>
<th>Policy</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimal pricing + investment</td>
<td>8.225</td>
</tr>
<tr>
<td>Optimal pricing + current investment</td>
<td>5.354</td>
</tr>
<tr>
<td>Current pricing + optimal investment</td>
<td>6.300</td>
</tr>
</tbody>
</table>
So we see:

- If we implement just the pricing part (durability tolls) we get 65% of the benefits of full optimality.
- If we implement just the investment part, we get 77% of the benefits of full optimality.
- It is an interesting question whether the political difficulties with these less-than-optimal policies would be less than with full optimality.
References
