Road Construction and Maintenance
The Full Story

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Introduction

So far we have:

- Discussed how to manage traffic on a road, how to determine the road’s optimal capacity (in standard-sized-lanes, \( w \)), and the associated congestion tolls to bring about the desired traffic level.
- Discussed how to design a maintenance policy for a road by choosing the optimal durability \( D \); and derived the associated durability tolls.

We now put the two dimensions (capacity and durability) together.

As always, we consider a 1-mile stretch of road.

We will assume that our problem is to select \( w \) and \( D \) to minimize total annualized system costs.

Optimal Durability + Lanes Combined (I)

System costs have the following components:

- Annual user (time) costs:

\[
\sum_t \frac{v \cdot q_t}{u_t(q_t, w)}
\]

- Annualized up-front public sector costs:

\[
r(k_0 + k_1w + k_2wD)
\]

- Annualized public sector periodic maintenance costs:

\[
\frac{r \cdot w \cdot k_m}{e^{rT} - 1}
\]

where \( T = N(D)/\lambda Q \) as before; \( u_t = \) speed; \( q_t = \) PCE’s in period \( t \);
\( Q = \) annual ESALs (loadings)

Optimal Durability + Lanes Combined (II)

Small, Winston and Evans (SWE) solve this problem under a few simplifications and additional assumptions

- Peak PCEs only; the peak lasts 500 hours per year.
- BPR travel-time function.
- Single value of time (\( w = \$7.50/\text{hour}, \) in \( \$\ 1982 \)).
- There is a complicated adjustment procedure to allow them to use the Keeler and Small (KS) road costs to arrive at a construction cost function that depends on durability \( D \) (which the KS results did not).
- Lane capacity = 1800 PCE’s per lane per hour (KS used 2000) on a freeway; 1080 on an urban arterial.
Optimal Durability + Lanes Combined (III)

So our problem is to select $w$ and $D$ to minimize

$$TSC = v \cdot q \cdot t(q, w) + r \left( k_0 + k_1 w + k_2 wD \right) + \frac{r \cdot w \cdot k_m}{e^{T/\lambda} - 1}$$

where:

- $q$ is peak PCEs and $Q$ is annual loadings (in ESALs)
- $t(q, w)$ is the travel-time per mile, given by a BPR function with suitable choice of parameters
- $T = N(D)/\lambda Q$, as before.

This is a two-variable optimization problem, and though it is more complicated than the separate one-variable problems we’ve considered up to now, it is straightforward to solve on a computer.

The Financial Question

We already have an idea what to expect:

1. We suspect that we may need more lanes, since peak speeds are lower than optimal (see the Optimal Capacity handout). However, this is not conclusive, since we could get higher speeds at existing capacity by imposing large congestion tolls to discourage peak usage.
2. We expect that the roads we build should be more durable (see the Designing Maintenance Policies handout).

We are also interested in the question of highway finance: whether a system of optimal congestion and durability tolls will cover all public sector road costs; and if not, how much of a subsidy from other sources (eg general taxation) will be needed.

Additional Data

- In addition to the data in the Designing Maintenance Policies handout we also need data on $k_0$, the fixed construction cost per mile: this is needed for the highway finance results even though it will not affect the optimization (since neither $w$ or $D$ are affected by $k_0$). SWE use:

<table>
<thead>
<tr>
<th>Road Type</th>
<th>Fixed cost $k_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban expressway</td>
<td>1,468,462</td>
</tr>
<tr>
<td>Urban arterial</td>
<td>871,599</td>
</tr>
</tbody>
</table>

- Other assumptions ($\lambda$, $r$, etc) are as in the earlier handout.

Results

The next slides show some of SWE’s results, for an urban (rigid) expressway and an urban (flexible) arterial. Each set of results is presented in two tables:

1. The first table shows the optimal physical characteristics of the roads, namely the optimal lanes ($w^*$) and durability ($D^*$), as well as the peak volume-to-capacity ratio.
   
I also attempt to estimate peak speeds. SWE don’t estimate the $\alpha$ parameter of the BPR function and hence can’t compute speeds. See Appendix for details. You should remember that these are only intended as estimates.

2. The second table shows the financial results from charging users the appropriate optimal congestion and durability tolls. We also show the annual cost and revenue totals.
Results – Urban Expressway — Physical

<table>
<thead>
<tr>
<th>Item</th>
<th>Low q</th>
<th>Medium q</th>
<th>High q</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assumption</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>q (peak PCEs)</td>
<td>1.33</td>
<td>2.00</td>
<td>2.67</td>
</tr>
<tr>
<td>Q (ESALs)</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>Construction</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$w^*$ (lanes)</td>
<td>2.02</td>
<td>3.03</td>
<td>4.04</td>
</tr>
<tr>
<td>$D^*$ (inches)</td>
<td>9.95</td>
<td>9.95</td>
<td>9.95</td>
</tr>
<tr>
<td>Peak q/c ratio</td>
<td>0.73</td>
<td>0.73</td>
<td>0.73</td>
</tr>
<tr>
<td>Estd speed (mph)</td>
<td>43.9</td>
<td>43.9</td>
<td>43.9</td>
</tr>
</tbody>
</table>

Results – Urban Expressway — Financial

<table>
<thead>
<tr>
<th>Item</th>
<th>Low q</th>
<th>Medium q</th>
<th>High q</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assumption</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>q (peak PCEs)</td>
<td>1.33</td>
<td>2.00</td>
<td>2.67</td>
</tr>
<tr>
<td>Q (ESALs)</td>
<td>0.25</td>
<td>1.00</td>
<td>0.25</td>
</tr>
<tr>
<td>Tolls (c/ relevant mile)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Congestion</td>
<td>14.5</td>
<td>14.5</td>
<td>14.5</td>
</tr>
<tr>
<td>Durability</td>
<td>1.2</td>
<td>0.4</td>
<td>0.6</td>
</tr>
<tr>
<td>Totals ($000/mile)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Revenues</td>
<td>196.1</td>
<td>294.1</td>
<td>392.2</td>
</tr>
<tr>
<td>Costs</td>
<td>250.2</td>
<td>378.2</td>
<td>491.5</td>
</tr>
<tr>
<td>Surplus</td>
<td>-5.7</td>
<td>-4.1</td>
<td>-2.7</td>
</tr>
</tbody>
</table>

Results — Urban Expressway : Commentary

- Current durability standards are appropriate for low loadings ($Q$). But when we see high loadings, durability levels (inches of concrete) should be about 30% higher.
- Remembering that the estimated speeds depend on an assumption about the free-flow travel speeds (see Appendix) it seems that with optimal investment and pricing, speeds would rise, but not substantially.
- Controlling congestion requires surprisingly low tolls (about $14c – 15c$ per PCE-mile, in $$1982$).
- Durability tolls are also low: at optimal D, even a fairly heavy truck generates only about 2.5 ESALs, so its durability toll would be at most $5c$ per mile.
- With optimal tolls (both congestion and durability) the highway sector would require a subsidy ranging from about $6000 per mile for a lightly used expressway, to $600 per mile for a heavily-used road.
Results – Urban Arterial — Physical

<table>
<thead>
<tr>
<th>Item</th>
<th>Low q</th>
<th>Low Q</th>
<th>Medium q</th>
<th>Medium Q</th>
<th>High q</th>
<th>High Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assumption</td>
<td></td>
<td>0.10</td>
<td>0.40</td>
<td>0.50</td>
<td>0.10</td>
<td>0.50</td>
</tr>
<tr>
<td>q (peak PCEs)</td>
<td>0.40</td>
<td>0.40</td>
<td>0.80</td>
<td>0.80</td>
<td>1.60</td>
<td>1.60</td>
</tr>
<tr>
<td>Q (ESALs)</td>
<td>0.10</td>
<td>0.50</td>
<td>0.10</td>
<td>0.50</td>
<td>0.10</td>
<td>0.50</td>
</tr>
<tr>
<td>Construction</td>
<td>1.00</td>
<td>0.99</td>
<td>2.00</td>
<td>1.98</td>
<td>4.00</td>
<td>3.96</td>
</tr>
<tr>
<td>w* (lanes)</td>
<td>4.97</td>
<td>6.27</td>
<td>4.97</td>
<td>4.97</td>
<td>4.97</td>
<td>6.27</td>
</tr>
<tr>
<td>D* (SN)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak q/c ratio</td>
<td>0.74</td>
<td>0.75</td>
<td>0.74</td>
<td>0.75</td>
<td>0.74</td>
<td>0.75</td>
</tr>
<tr>
<td>Est. speed (mph)</td>
<td>24.3</td>
<td>24.4</td>
<td>24.3</td>
<td>24.4</td>
<td>24.3</td>
<td>24.4</td>
</tr>
</tbody>
</table>

Results – Urban Arterial — Financial

<table>
<thead>
<tr>
<th>Item</th>
<th>Low q</th>
<th>Low Q</th>
<th>Medium q</th>
<th>Medium Q</th>
<th>High q</th>
<th>High Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assumption</td>
<td></td>
<td>0.10</td>
<td>0.50</td>
<td>0.10</td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>q (peak PCEs)</td>
<td>0.40</td>
<td>0.40</td>
<td>0.80</td>
<td>0.80</td>
<td>1.60</td>
<td>1.60</td>
</tr>
<tr>
<td>Q (ESALs)</td>
<td>0.10</td>
<td>0.50</td>
<td>0.10</td>
<td>0.50</td>
<td>0.10</td>
<td>0.50</td>
</tr>
<tr>
<td>Tolls (¢/relevant mile)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Congestion</td>
<td>14.8</td>
<td>15.1</td>
<td>14.8</td>
<td>15.1</td>
<td>14.8</td>
<td>15.1</td>
</tr>
<tr>
<td>Durability</td>
<td>1.0</td>
<td>0.2</td>
<td>2.0</td>
<td>0.5</td>
<td>4.0</td>
<td>0.5</td>
</tr>
<tr>
<td>Totals ($000/mile)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Revenues</td>
<td>60.1</td>
<td>61.6</td>
<td>120.1</td>
<td>123.1</td>
<td>240.3</td>
<td>246.3</td>
</tr>
<tr>
<td>Costs</td>
<td>88.3</td>
<td>90.1</td>
<td>171.0</td>
<td>174.6</td>
<td>336.4</td>
<td>343.6</td>
</tr>
<tr>
<td>Surplus</td>
<td>-4.5</td>
<td>-4.3</td>
<td>-3.5</td>
<td>-3.0</td>
<td>-1.4</td>
<td>-0.5</td>
</tr>
</tbody>
</table>

Results — Urban Arterial : Commentary

- Recalling that an average arterial now has a D-value (structural number) of about 4.2, it seems that arterials with low loadings (Q) are somewhat under-built (optimal D is about 5) but significantly underbuilt when there is a lot of heavy truck traffic (optimal D is then about 6.3).
- It is a bit more difficult to make a statement about the impact on speeds (since I’m not confident that I know currently observed speeds on urban arterials), but possibly speeds would not change much.
- Congestion tolls on arterials are comparable to those on expressways (about 15¢ per PCE-mile).
- Durability tolls are also low. In the worst case they come to 4¢ per ESAL-mile; and for a 2.5-ESAL truck would amount to only about 10¢ per mile.
- The arterial road system also requires a subsidy, ranging from about $4500 per mile (lightly used road) to $500 per mile for a heavily used road.
Final Policy Question (I)

Here’s where we are. We know:

- Cars vastly outnumber trucks on most highways.
- So congestion problems are mostly due to cars.
- Cars need lanes.
- Trucks do essentially all the road damage.
- Trucks need durability.

Final Policy Question (II)

So why not have two road systems:

- A multi-lane, low-durability system for cars.
- A durable, but narrow (= few lanes) system for trucks.

Final Policy Question (III)

When would this be a good idea?

- Write $C(q, Q)$ for the (annualized) cost to provide a road supporting $q$ annual PCEs and $Q$ annual ESALs
- Then the separate-systems idea is good if:
  
  $[C(q, 0) + C(0, Q)] < C(q, Q)$
  
  — that is, if the cost of running two separate road systems $(C(q, 0) + C(0, Q))$ is less than the cost $(C(q, Q))$ of running one combined system.

Economies of Scope

- Economists have defined the notion of economies of scope to describe when joint production is better than separate production.
- The degree of economies of scope is:
  
  $S_C = \frac{[C(q, 0) + C(0, Q)] - C(q, Q)}{C(q, Q)}$
  
  - This is the percentage change in going from separate to joint production.
  - If $S_C > 0$ we have economies of scope: the costs of separate provision of lanes and durability are more than joint production.
  - If $S_C < 0$, we have diseconomies of scope: the costs of producing lanes and durability together are more than the costs of producing them separately.
**Findings**

- SWE find diseconomies of scope, ranging from about 6% to 10% for both expressways and arterials.
- That is, separate production of road width and durability costs between 6% and 10% less than the cost of producing them together.
- This supports the 2-systems idea: wide but thin roads for cars and thick but narrow roads for trucks.
- It therefore seems to be wasteful to build all roads to withstand truck traffic, which is the current approach.

**But Does It Matter?**

- Given that the road network is already in place, it may not make sense to think of re-envisioning it with separate lanes for cars and trucks, especially if we need to build more lanes.
- To that extent, the durability-only model is probably the most relevant. The optimal congestion tolls are then the tolls associated with the given $w$ (and equilibrium traffic).
- However, planners do sometimes need to build completely new roads from scratch, and in those cases, especially for expressways, it may make sense to consider the impact of diseconomies of scope in road construction.
- But for arterials, even in the case of new construction, it is not clear that there is a viable way to build separate systems, one for cars and one for trucks.

**Appendix: Times and Speeds (I)**

- SWE do not specify the complete BPR function (they don’t need to). But they assume that if $t(v/c)$ is the travel time as a function of the volume-to-capacity ratio, then
  
  $$t(1) - t(0) = 1$$

  See footnote (d) to Table 6–1.

  - Given that we can write the BPR function as
    
    $$t = \alpha + \gamma \left(\frac{v}{c}\right)^k$$

    their assumption implies that $\gamma = 1$.

  - And as usual we have $\alpha = t(0)$, the travel time when traffic flows freely ($v/c = 0$). So all we need to do to estimate speeds is make an assumption about the free-flow travel time or speed.

**Appendix: Times and Speeds (II)**

In the tables shown above, I assume that:

- **Expressways**: free-flow travel speed is 65 mph, so the free-flow travel time is $65/60 = 1.0833$ and
  
  $$t = 1.0833 + \left(\frac{v}{c}\right)^{4.5}$$

- **Arterials**: given traffic lights, we assume that the free-flow travel speed is 30 mph, so the free-flow travel time is $30/60 = 2$ and
  
  $$t = 2 + \left(\frac{v}{c}\right)^2$$

  These allow us to calculate the estimated speeds shown in the tables. But remember that these are not necessarily the speeds from SWE.
References


Appendix - Price Changes

- Rough estimate of price changes for road construction costs:
  - 1972 – late 2013 (relevant to KS): 7.22
  - 1982 – late 2013 (relevant to SWE): 2.64
  - Source: Caltrans

- General consumer price index (relevant to values of time):
  - 1972 – early 2014: 5.67
  - 1982 – early 2014: 2.48
  - Source: Online Dollar Times Inflation Calculator