Road Economics

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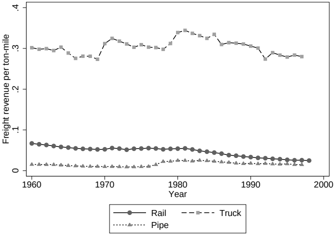
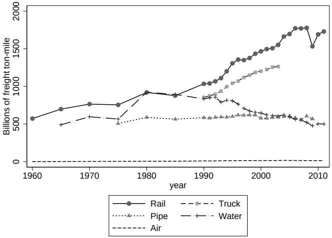
How to plan a road

- In 2022, Ukraine exported about 54m tons of goods by sea. Round this up to 64m tons to make my math easier later.
- Suppose half of exports originate in Dnipro and went via ports that are no longer available. These good must now find their way to Odessa.
- Suppose one quarter of these goods go by truck and three quarters go by rail. Thus, $\frac{1}{2} \times \frac{1}{4} \times 64m$ tons $= 8m$ tons of goods must travel by road from Dnipro to Odessa.
- By the most direct route, this is 450km. To minimize the cost of moving this freight, how wide, and how durable should this road be?

Why would 1/4 of goods travel by truck? I



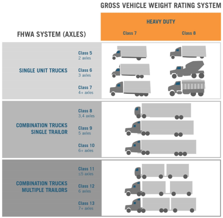
$/ton mile by mode (US) (Redding and Turner, 2015)



ton miles by mode (US)(Redding and Turner, 2015)

- Moving goods by rail is much cheaper than by truck.
- But trucks dominate for manufactured goods.
- Grain, ore, commodities go by rail. More valuable (per ton) manufactured goods go by truck.
- $\frac{1}{4}$ by truck is a bit less than the US share.

ESALs



- ESAL = 'Equivalent Standard Axle Load'. It is equal to the damage caused by a single axle with an 18 ton load.
- A fully loaded combination truck carries about 25 tons of cargo = 1 ESAL.
- Damage increases with the cube of axle weight. The configuration of the truck, the number of axles, the distance between them, are also important.
- Assume freight moves in five axle combination trucks carrying 25 tones of freight = 1 ESAL.
- Aside: 2000 cars are about one ESAL. Ignore them.

How many lanes?

- Moving 8m tons of freight, in 25 tons truckloads requires about 300k truckloads/year, about 1000/day.
- A single lane can carry about 2000 cars/hour, regardless of speed. People drive 2s apart and $(3600 s/hour)/2s = 1800$.
- Trucks need more room. Say 10s (guess) or 360 per hour.
  $\Longrightarrow$ A single lane at full capacity can carry 1000 trucks in three hours.
  $\Longrightarrow$ A single lane is enough to move our freight, with lots of capacity left over.
- Add a passing lane for 1km out of 5, so our average width is 1.2 lanes.
- 450km $\times$ 1.2 $\times$ out and back $=$ 1080 lane km of road.

How wide are lanes? I

- Cost is about proportional to width.
- At 12ft$=$4m can have 80-100kph speed of travel.
- At 10-11ft$=$3.5m can have 60-80kph.
- Dnipro to Odessa is 900k round trip. One day at 100kph. Two at 60kph.
- A narrower road means we need twice as many trucks.
- With 10% out of service, this means 2200 vs 1100.
- Trucks are about 100k$ and depreciate about 10%/year. So a wider road saves 10%$\times$ 100k$\times$ 1000 trucks$=$ 10m$/year.
- 10m$/year divided by 1080km means the wider road saves about 9200$per year per lane kilometer. Is this worth a 20% increase in costs? (12ft/10ft)?

How wide are lanes? II

- The benefit of faster travel/fewer trucks is *probably* tiny compared to construction costs. Let's build the narrower, slower, road.
- I'm ignoring other operating costs and value to cars.
- Should we think about reduced costs resulting from shorter transit times? Probably not, but it matters for boats.

Durability I

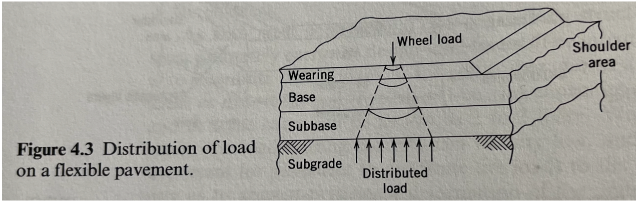


Figure 4.3 Distribution of load on a flexible pavement.

(Mannering and Washburn, 2020)

The object of the road is to distribute the loads that pass over from the wearing surface to the base below so that nothing moves. If the road receives too heavy a load, it moves, cracks, and then starts to fall apart.

Durability II

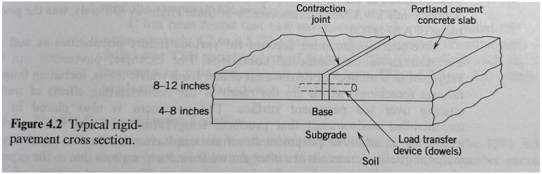


Figure 4.2 Typical rigid-pavement cross section.

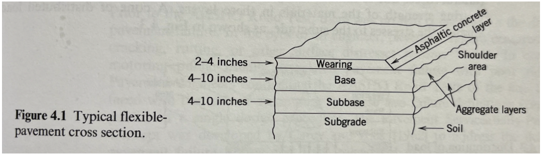


Figure 4.1 Typical flexible-pavement cross section.

(Mannering and Washburn, 2020)

- There are two main road technologies, ‘flexible’, i.e., asphalt, and ‘rigid’, i.e., concrete.

Durability III

- Their durability is measured by ‘structural number’.
- Each inch of concrete counts as one unit of structural number.
- Each inch of asphalt counts as 0.4 units of structural number.

Durability IV

Table 4.5 Structural-Layer Coefficients

Pavement component	Coefficient
Wearing surface	
Sand-mix asphaltic concrete	0.35
Hot-mix asphaltic (HMA) concrete	0.44
Base	
Crushed stone	0.14
Dense-graded crushed stone	0.18
Soil cement	0.20
Emulsion/aggregate-bituminous	0.30
Portland cement/aggregate	0.40
Lime-pozzolan/aggregate	0.40
Hot-mix asphaltic (HMA) concrete	0.40
Subbase	
Crushed stone	0.11

(Mannering and Washburn, 2020)

- Here is a little more on structural number.
- We've chosen number of lanes and lane width.
- We just need to choose durability, i.e. structural number.

Discount Present Value Theorem

- Let r be the interest rate. Define the discount factor
- Let time be discrete, so $t = 1, 2, 3, ...$
- Then the present value of receiving x for N periods starting today is

$$\sum_{t=0}^{N-1} = \frac{1-\delta^N}{1-\delta}$$

- ... and the present value of receiving x forever starting today is

$$\sum_{t=0}^{\infty} = \frac{1}{1-\delta}$$

For example, if $r = 0.05$ then $\delta \approx 0.95$ and the 10k year savings from 12 foot vs 10 ft lanes (from fewer trucks) is worth

$$\sum_{T=0}^{\infty} \delta^T \times 10,000\$ = 200,000\$$$

per lane kilometer.

Optimal Durability

$$
\begin{aligned}
D &\sim \text{Durability, i.e., structural number} \\
r &\sim \text{interest rate} \\
\delta &\sim \frac{1}{1+r} \\
Q &\sim \text{ESALs per year of service} \\
T(D,Q) &\sim \text{Years of service for durability } D \text{ at ESALs } Q \\
W &\sim \text{Width in lanes} (= 1.2) \\
M &\sim \text{Maintenance cost per year per lane km} \\
&= M(Q,D) \\
K &\sim \text{Construction cost per lane km} \\
&= K(D)
\end{aligned}
$$

Cost to provide Q ESALs for W lanes and $T(Q, D)$ years

$$
\begin{aligned}
c(D) &= WK(D) + \sum_{t=0}^{T(D,Q)-1} \delta^t WM(Q, D) \\
&= WK(D) + \frac{1-\delta^{T(D,Q)}}{1-\delta} WM(Q, D) \\
&= W\left[K(D) + \frac{1-\delta^{T(D,Q)}}{1-\delta} M(Q, D)\right]
\end{aligned}
$$

- What happens after $T(D, Q)$ years? The road is worn out and we start again.
- Why do we want a bigger D? To delay the 'start again cost', A.K.A., 'continuation value'.
- Why is this good? Discounting.

- Let $\gamma = \delta^{T(D,Q)}$. Suppose that when the road wears out we choose the same D again, and again.
- Then the total cost of providing Q ESALs forever is,

$$
\begin{aligned}
C(D) &= c(D) + \gamma c(D) + \gamma^2 c(D) + \gamma^3 c(D) + ... \\
&= \sum_{\tau=0}^{\infty} \gamma^{\tau} c(D) \\
&= \frac{1}{1-\gamma} c(D)
\end{aligned}
$$

- Substituting from the definition for γ and for $c(D)$, we get

$$
C(D) = \frac{1}{1-\delta^{T(D,Q)}} W \left[K(D) + \frac{1-\delta^{T(D,Q)}}{1-\delta} M(Q,D) \right]
$$

- How do we choose D? We would like to minimize the cost of providing road services Q.
- That is, we want to solve,

$$\min_D \frac{1}{1-\delta^{T(D,Q)}} W \left[K(D) + \frac{1-\delta^{T(D,Q)}}{1-\delta} M(Q,D) \right]$$

  This is a single variable, unconstrained optimization problem in D. Take the FOC, set it equal to zero and solve.
- This is easy in theory. In practice, we need to know functional forms for $M(Q,D)$, $T(Q,D)$, and $K(D)$.
- This is hard to do in practice. This is exactly what Small and Winston (1988) do.

TABLE 2—OPTIMAL DURABILITY

Q (1000s ESALs/yr)	D^* (inches slab thickness or structural number)			
	Rigid Pavements		Flexible Pavements	
	Ours[a]	AASHO[b]	Ours[a]	AASHO[b]
250	8.8	8.0	5.3	5.1
1,000	11.5	9.8	6.4	6.2
2,500	13.8	11.2	7.3	6.9

[a] $N(D)$ is computed using our estimates of modified equation (11), as given in Table 1.
[b] $N(D)$ is computed using AASHO's estimates of equations (9)–(11), as reported in Highway Research Board (1962, pp. 40, 152).

- Recall, we have 1000 trucks/day $=$ 1000 ESALs/day. This is 300k/year.
- The first row of this table gives optimal D for 250k ESALs/year, pretty close to what we need.
- The first two columns give thickness of rigid pavement. Third and fourth are structural numbers for flexible pavement.

- For each pavement type, Small and Winston (1988) give two estimated, theirs and the one from the “American Association of State Highway [and Transportation] Officials” (AASHTO). This is a professional association for highway engineers.
- From Column 3, row 1, the best structural number for a flexible road is 5.3. This is $5.3/0.4 = 12.75$ inches of asphalt.

Thus, we have characterized the cost minimizing road to carry freight from Dnipro to Odessa; 1.2 lanes each way, narrow 3.5m lanes, and 13 inches of asphalt.

A few comments

- If trucks return to Dnipro empty, what does this mean? ESALs for an empty truck are probably about 0.25.
- In the US, the construction of lane kilometer of highway often costs more than 10m dollars. It will likely be cheaper in Ukraine because labor will be cheaper and there will less environmental regulation.
- Small and Winston (1988) base their calculations on US cost parameters, like cost of materials and interest rate from 1988.
- At even 500k$ per lane km, our project would cost 500m $. At this price, it probably makes sense to redo Small and Winston for Ukraine specific values. NB: At this price, we probably want wider lanes.

- I've abstracted from lots of details; how ESALs vary with axle spacing; how much crushed rock contributes to the structural number. Mannering and Washburn (2020) has all this information, or citations to AASHTO publications that do.
- The main idea/intution of the calculation I've presented is the same as in Small and Winston (1988).
- Should we adjust Q downward to allow for traffic spreading out on passing lanes? No. The single lane sections still carry the full load.

Mannering, F. L. and Washburn, S. S. (2020). *Principles of highway engineering and traffic analysis*. John Wiley & Sons.

Redding, S. J. and Turner, M. A. (2015). Transportation costs and the spatial organization of economic activity. *Handbook of regional and urban economics*, 5:1339–1398.

Small, K. A. and Winston, C. (1988). Optimal highway durability. *The American economic review*, 78(3):560–569.