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Impact of Super Heavy Load Vehicles on Transportation Infrastructure: Economic Aspects

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Abstract Sometimes, there is a need to transport very heavy equipment, so heavy that the resulting load is several times larger than the maximal load that the corresponding road segment was designed to withstand. Such super heavy load vehicles decrease the remaining service life of the road segment, and sometimes even make the segment unusable and needing repairs. In both cases, the need for earlier-than-expected repairs means additional costs. It is therefore desirable to estimate the expected value of this additional cost. In locations where the owner of the super heavy load vehicle pays for the vehicle passage, this is necessary to decide how much to charge the owner. In other locations, where the agreement is that the cost of additional repairs comes from the additional taxes that the vehicle owners pay, such an estimate is needed to the road owners – e.g., to the county or to the state – so as to select the route for which the expected additional cost of repairs is the smallest.

Keywords economics · transportation infrastructure · super heavy load vehicles

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1 Formulation of the Problem

What are Super Heavy Load vehicles. Specifications for new roads and for road maintenance and repairs include limits on the weight (and other parameters) of the vehicles that will be traveling along these roads. A road is then designed in such a way that with traffic by vehicles that fit within these limits, the road will stay operational for a certain pre-determined period of time T .

Once the road is built, sometimes, a previously unexpected need appears to use vehicles which are much heavier than the current limit. For example, in Texas, the discovery and resulting exploration of oil fields result in the need to move very heavy machinery and equipment such as well servicing units, power transformers, electric generators, etc. Of course, this super heavy equipment requires special vehicles, with a large number of axles, but still the load on each axle far exceeds the limits used to design the road. Such vehicles are known as *Super Heavy Load vehicles*.

Since the effect of super heavy load vehicles far exceeds the load for which the road was built, the impact of a super heavy load vehicle on the road can be drastic, even after a single passage of the vehicle:

- in all the cases, the road's remaining service life decreases, sometimes drastically, and
- in some cases, some segments of the road become so damaged after the passage of a super heavy load vehicle that they are no longer usable and needs to be immediately repaired.

Comment. To understand the scope of the problem, it is important to mention that the need for super heavy load vehicles is not just a once-in-while event: for example, in Texas during the period from 2017 to 2020 there

were more than 8000 such events – which amounts, on average, to 4 such events per day.

Technical aspects of the problem. Because of the serious impact of super heavy load vehicles on the transportation infrastructure, it is important to be able to predict this effect as accurately as possible.

There has been a lot of research in this direction; see, e.g., [1–22]. The resulting formulas and algorithms help to predict both:

- the expected decrease in the remaining service life of the affected road segments, and
- the probability of the immediate failure of these road segments.

Economic aspects of the problem. Every time a super heavy load vehicle passes through a road segment, the remaining service life of this segment decreases – which necessitates additional costs. When a road segment becomes immediately damaged, this leads to even more costs.

There are two different ways to deal with such costs:

- In some locations, the expected cost of additional repairs is charged to the company that operates the super heavy load vehicles. In such situations, it is important to provide an accurate prior estimate of the expected cost to the company.
- In other locations, the agreement is that the additional costs of road repair and maintenance are more than compensated by the taxes that the company pays. In such case, it is still important to provide a prior estimates of the expected cost, so that the road owners – which is, usually, the local government or the state or the federal government – will be able to decide which of the possible super heavy load vehicle routes will lead to the least expensive road repairs.

In both cases, we need to be able to combine the estimates:

- of the remaining service life and
- of the probability of the immediate failure

into a single estimate of the expected cost.

What we do in this paper. In this paper, we explain how to estimate the overall cost based on the estimates:

- of the remaining service life and
- of the probability of the immediate failure.

2 Cost Estimates

Technical estimates: a brief description. As we have mentioned, technical estimates takes care of both types of possible road damage.

First, there is a possibility that the road segment will be made unusable and will thus need repairs right after the super-heavy load vehicle passed through this road. Let p denote the probability that this unfortunate event happens.

Second, even when the road segment remains usable, the fact that this road segment is exposed to stress beyond the one for which it was designed causes some additional damage to the road, eventually decreasing the time this road will be usable without costly repairs. This damage can be gauged by the decrease in the remaining service life, from the original value t to a somewhat decreased value $(1 - \alpha) \cdot t$. The coefficient α describes the severity of the damage: the larger the damage, the larger this coefficient α .

How to combine these two estimates: analysis of the problem. How can we combine the two values p and α into a single economic criterion?

Let C be the cost of repairing the given road segment, and let T be the usual period between the two repairs – so that if we perform a repair, the road segment can be explored for T more years before the next repair will be needed.

Let q be the discount – so that \$1 next year can be obtained by $q < 1$ dollars this year. This value is related to the interest rate:

- if the interest rate is i ,
- this means that \$1 now is equivalent to $(1+i)$ dollars next year.

Thus, \$1 next year is equivalent to $\frac{1}{1+i}$ dollars now,

so $q = \frac{1}{1+i}$.

Similarly, we can conclude that paying \$1 after y years is equivalent to paying the amount $\frac{1}{(1+i)^y} = q^y$ now.

If no super-heavy vehicles are passing through the considered road segment, then we will need:

- the first repair t years from now,
- then another repair $t + T$ years from now,
- then yet another one $t + 2T$ years from now, etc.

For each of these repairs, we spend C dollars. So, taking discounting into account, the equivalent today's cost C_0 of all future repairs is equal to

$$C_0 = q^t \cdot C + q^{t+T} \cdot C + q^{t+2T} \cdot C + \dots = q^t \cdot C \cdot (1 + q^T + q^{2T} + \dots). \quad (1)$$

By using the known formula for the sum of the geometric series

$$1 + q^T + q^{2T} + \dots = \frac{1}{1 - q^T},$$

we get

$$C_0 = \frac{C}{1 - q^T}. \quad (1a)$$

If the road segment is damaged right now, then:

- we will need a repair right now,
- we will need the next repair at time T ,
- then yet another repair at time $2T$, etc.

So, the overall cost C_d of repairs becomes equal to:

$$C_d = C + q^T \cdot C + q^{2T} \cdot C + \dots = C \cdot (1 + q^T + q^{2T} + \dots). \quad (2)$$

Comparing the formulas (1) and (2), we conclude that

$$C_d = C_0 \cdot q^{-t}. \quad (3)$$

If the road segment's expected service life is decreased from t to $(1 - \alpha) \cdot t$, then we will need:

- a repair at time $(1 - \alpha) \cdot t$,
- then a repair at time $(1 - \alpha) \cdot t + T$,
- then a repair at time $(1 - \alpha) \cdot t + 2T$, etc.

Thus, in this case, the overall cost C_α of all the repairs is equal to:

$$C_\alpha = q^{(1-\alpha) \cdot t} \cdot C + q^{(1-\alpha) \cdot t + T} \cdot C + q^{(1-\alpha) \cdot t + 2T} \cdot C + \dots = q^{(1-\alpha) \cdot t} \cdot C \cdot (1 + q^T + q^{2T} + \dots). \quad (4)$$

Comparing the formulas (1) and (4), we conclude that

$$C_\alpha = C_0 \cdot q^{-\alpha \cdot t}. \quad (5)$$

In general:

- with probability p , we have the immediate road failure, and
- with the remaining probability $1 - p \approx 1$, we have a decrease in the road's remaining service life.

So overall, the expected cost of repairs is equal to:

$$C_e = p \cdot C_d + C_\alpha = C_0 \cdot (p \cdot q^{-t} + q^{-\alpha \cdot t}). \quad (6)$$

Resulting estimate. Thus, in comparison to the original cost C_0 , the passing of a super-heavy load vehicle increases the expected cost of the current road segment's repairs by the following amount:

$$\Delta C = C_e - C_0 = C_0 \cdot (p \cdot q^{-t} + q^{-\alpha \cdot t} - 1), \quad (7)$$

i.e., equivalently, by

$$\Delta C = \frac{C}{1 - q^T} \cdot (p \cdot q^{-t} + q^{-\alpha \cdot t} - 1). \quad (8)$$

Comment. The formulas (7) and (8) describe the expected value of the additional cost that driving a super-heavy load vehicle will incur – and thus, this should be the cost that the owner of this vehicle should pay to the owner of this road segment.

In situations in which there is no compensation to the owner of the road segment, the formulas (7) and (8) can be used to decide whether to allow the truck to pass: we should allow it if the additional expected cost does not exceed a certain small percentage p_0 of the original expected cost C : $\Delta C \leq p_0 \cdot C$, i.e., equivalently, if

$$p \cdot q^{-t} + q^{-\alpha \cdot t} - 1 \leq p_0. \quad (9)$$

In both types of situations, the left-hand side

$$L \stackrel{\text{def}}{=} p \cdot q^{-t} + q^{-\alpha \cdot t} - 1 \quad (10)$$

of the inequality (9) is the proper way of combining the information about the two possible types of damage.

Numerical example. Let us consider the case when $t = 20$ years, the probability of immediate serious damage is $p = 5\%$, the overall damage is $\alpha = 0.1$, and the interest rate is $i = 3\%$, so that $q^{-1} = 1 + i = 1.03$.

In this case, $\alpha \cdot t = 2$, and

$$L = 0.05 \cdot 1.03^{20} + 1.03^2 - 1 =$$

$$0.05 \cdot 1.806 \dots + 1.061 \dots - 1 = 0.151 \dots$$

So:

- if we set p_0 to 20%, we should allow this passing, while
- if set p_0 to 15%, we should not allow it.

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Human and animal ethical standards This article does not contain any studies with human participants or animals performed by any of the authors.

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