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# The cost of relying on the wrong power—road wear and the importance of the fourth power rule (TP446)

Richard Johnsson

*Katarina Jagellonikas väg 14, SE-19330 Sigtuna, Sweden*

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**Abstract**

This paper investigates the effect on road wear and deformation of alternatives to the Fourth Power Law in a computable general equilibrium model of Sweden. The alternatives considered are the first through fifth powers, and the results indicate that the results are similar in all cases but when the first power is employed. This follows from the fact that designing the charge according to the first power amounts to a weight-distance charge rather than an axle-weight-distance. The paper also investigates the cost of designing a charge according to the wrong power, i.e. not according to the true relationship between road wear and road use. The results indicate that the cost of choosing the wrong power is relatively small, but slightly higher in the case of the first power. Indeed, there are several implicit costs that seem to have to be taken into account when implementing a charge according to the former power, i.e. a weight-distance charge.



*Keywords:* Road wear; Fourth power rule; Charge

## 1. Introduction

When it comes to road wear and deformation, it is perhaps surprising how influential the American Association of Highway and Transportation Officials (AASHO, 1962) study, conducted back in the 1950s and 1960s, still is. The study found that road wear and deformation was largely related to axle weight rather than vehicle weight. The study also found that the relationship of road wear and deformation to axle weight was highly non-linear and the so-called Fourth Power Rule emerged.

Using the same data set as the original AASHO study, the relationship has been re-estimated and largely confirmed by Small et al. (1989) and other studies have extended the original study by including new axle configurations. But no new empirical data similar to, and as extensive as, the AASHO data has been collected. Instead, yet other studies have highlighted other characteristics affecting the relationship between road wear and deformation and the use of the road. These studies have for example focused on tyre characteristics, suspension systems, axle spacing, the use of liftable axles and the use of triple axles (tridems)[1]. But considering the changes in truck characteristics as well all this new research that have appeared since the original AASHO study, it is tempting to ask whether the famous Fourth Power Rule still is valid? Is it really a fourth power, or is it rather a third if the effect of the axle spacing is included? etc.

National road administrations in many countries are considering the possibility to use an axle weight-distance related kilometer charge to cope with costs related, for example, to road infrastructure and maintenance. It has been suggested that there is no real alternative to the AASHO Fourth Power Rule (see Martin (2000, p. 90)). But is it the 'right' power rule? What if the true relation is better represented by, for example, a second power rule? This study will analyse the implications of the design of a charge according to a specific power rule, while allowing for the possibility that the true relation is represented by another power. This will provide an indication as to whether the issue is of any practical interest at all. The analysis will be made by implementing a charge designed according to the first through the fifth power and for 10 different truck categories, in a computable general equilibrium (CGE) model of Sweden.

In Section 2 the study proceeds to discuss a number of aspects, beside axle-weight, that have been suggested as affecting road wear and deformation. In Section 3 the charge

*E-mail address:* richardcbjohnsson@tiscali.se

[1] See for example FHWA (1995), DETR (2000), and Kenis and Cobb (1990).

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is calculated, and in Section 4 the simulation results are presented. Section 5 concludes the study.

## 2. The fourth power rule?

The results of the AASHO (1962) study and the Fourth Power Rule can be summarized, as in Small et al. (1989, p. 11): "Two technological facts are crucial to understanding road wear. First, the equivalence factor for an axle rises *very* steeply with its load—roughly as its third power. […] Second, it is the weight per axle that matters, not total vehicle weight". Although Small et al. question the AASHO result by suggesting "our estimates show a somewhat less steep relationship between pavement life and axle load—closer to a third-power principle than to the fourth-power principle conventionally used…", they are referring to rigid pavements. For flexible pavements, such as the asphalt used in Sweden, the AASHO rule of thumb, the Fourth Power Law, seems to be verified by Small et al. (1989). It is also verified by a report to the Swedish Government back in the 1960s, a report that designed the kilometer charge introduced in 1974 and abolished in 1993[2]. The report noted that the exponent (i.e. the power) fluctuates widely depending on the type of road body, but that a study had arrived at an exponent of 3.9 for asphalt roads when applying the AASHO formula under Swedish conditions.[3]

Since the AASHO study, however, several other factors have been identified as influencing the road wear. These include tyre characteristics, suspension systems, the use of liftable axles, axle spacing and the use of triple axles (tridems) and the fact that the road types are a major determinant of the exponent. And there have naturally been many changes in truck characteristics since the AASHO study.

First of all, for commercial considerations, tyres have generally become lighter, smaller in diameter and able to carry a greater load. This has for example resulted in the use of radial instead of bias-ply tyres, higher tyre pressure and more frequent use of dual tyres. When it comes to tyres, it is a known fact that higher tyre pressure reduces the size of a tyre's 'footprint' on the pavement, so that the weight of the wheel is distributed over a smaller area, suggesting greater road wear. The wide single tyres bring about savings in fuel costs but might result in higher road wear than otherwise identical dual tyres. On the other hand, although dual tyres could be expected to cause less road wear than single tyres, in reality one of the tyres may often be overloaded due to unequal tyre pressures, uneven tyre wear, or pavement crown. This to some extent offsets the expected advantage of dual tyres. Another effect of dual tyres is the effect of randomness in the lateral placement of the truck on the road. This means that the single tyre often wander sideways over the lane, spreading the wear out sideways. A dual tyre lessens this 'positive' effect. FHWA (1995) summarizes this in the following way (p. 16): "Taking all of these findings into consideration suggests that the relative damage potential [of single tyres] is much less than commonly believed, and conceivably the wide base [single] tires might be less damaging than duals." This is a conclusion not found in for example DETR (2000), hinting at the major uncertainties in the field.

A second truck characteristic that has changed since the AASHO study is the suspension systems. Again quoting FHWA (1995): "As a heavy truck travels along the highway, axle loads applied to the pavement surface fluctuate above and below their average values. […] On the assumption that the pavement wear effects of dynamic loads are similar to those of static loads and follow a fourth-power relationship, increases in the degrees of fluctuation increase pavement wear." Thus, better suspension systems might decrease the road wear, but, as noted in DETR (2000), this is for example conditional upon the suspension system being "maintained at a specified level in order to maximize those benefits" (p. 70). Thus, there is a large uncertainty in how the suspension system might affect road wear and the Fourth Power Rule.

A third truck characteristic influencing the road wear that was not accounted for in the AASHO study is the use of liftable axles. Liftable axles "provide the vehicle operator with the opportunity of reducing tyre wear and fuel consumption at times when the vehicle is substantially less than fully laden", but there is "a risk that the lift axle can be misused or abused" (DETR, 2000, p. 76). This is because it is conceivable that an operator will take the opportunity to reduce tyre wear and fuel consumption also when the truck is fully loaded. FHWA (1995) also mentions the use of liftable axles to get around the—often employed—charges determined by the combination of weight and the number of axles. Charging the liftable axles as if they were rigid axles could of course, solve this problem. But that perhaps introduces other problems. Anyhow, there is a great uncertainty in this area as well.

Fourth, the axle configuration also affects road wear in different ways. For example, it is unlikely that axle spacing affects rutting, but is more likely to affect the fatigue. If axles are placed close enough together, they start to act as an entity and it is suggested in the FHWA (1995) study (p. 18) "that the AASHTO[4] esal [equivalent standard load] values appear to understate the damaging effect of dual and triple axles in comparison to single axles." FHWA (1995) also mentions studies that question the AASHTO (1993) values for tridems. The road wear factor for tridems used in the present study are based on Kenis and Cobb (1990). Hence, there is a great deal of uncertainty in this field, too.

[2] See SOU 1969:45.

[3] The coefficients in the Small et al. study were 3.241 for rigid pavements and 3.652 for flexible pavements. In a study by NCHRP (1993, p. 12) it was found that 'Rutting damage is proportional to axle load, and fatigue is roughly proportional to load raised to the fourth power'. The results of the Swedish study can be found in SOU 1969:45 p. 134.

[4] American Association of State Highway and Transportation Officials (AASHTO) is the predecessor to AASHO.

Table 1
The kilometer charge in SEK per vehicle kilometer

| Scenario | Exponent | Local | | | Regional | | | | | Long-distance | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | L2 | L3 | L4 | LS21 | LS22 | LS23 | LS32 | LS33 | LS34 | LS44 |
| Scenario 1 | 1 | 0.47 | 0.44 | 0.37 | 0.73 | 0.93 | 0.9 | 0.85 | 0.75 | 1.00 | 0.93 |
| Scenario 2 | 2 | 0.55 | 0.48 | 0.32 | 0.87 | 1.06 | 1.00 | 0.89 | 0.72 | 1.22 | 1.06 |
| Scenario 3 | 3 | 0.57 | 0.47 | 0.24 | 0.90 | 1.05 | 0.96 | 0.80 | 0.62 | 1.28 | 1.05 |
| Scenario 4 | 4 | 0.60 | 0.46 | 0.17 | 0.92 | 1.02 | 0.93 | 0.72 | 0.55 | 1.32 | 1.04 |
| Scenario 5 | 5 | 0.63 | 0.45 | 0.12 | 0.94 | 1.00 | 0.90 | 0.65 | 0.50 | 1.35 | 1.02 |

Finally, the value of the exponent seems to be determined to a high degree by the road type. DETR (2000) refers to results where the exponent has been allowed to vary between three and nine, that is, to a very high degree. In the Swedish study referred to above, the exponent for road types built on different types of soil ranges from 1.16 to 8.52 with a weighted average of 3.30 (SOU 1969:45, pp. 136–7). The exponent seems to be lower where most of the transport by heavy truck is conducted (which in turn is a reflection of the fact that roads are often better where traffic is heavy). However, there might be exceptions to the last point[5]. But let us now proceed to Section 3, which outlines how the charge is calculated.

## 3. The charge

The charge is calculated according to the first, second, third, fourth and fifth power. However, this is not as straightforward as it might seem and requires some explanation. First of all, the number of so-called equivalent standard axle loads (esals) for each truck category used in the study (L2–L44) is calculated according to

$$\mathrm{ESALS}_j = \sum_i x_i^{\mathrm{exp}} \tag{1}$$

where the truck category $j$ is the sum of the esal of each individual axle $i$ and where the esal of each individual axle, $x^{\mathrm{exp}}$, is the quotient between the actual axle weight and the standard axle of 8.172 metric tonnes (18 kip) raised to the exponent in question (1st, 2nd, 3rd, 4th or 5th). Second, each truck category traveled $z$ km the year in question. Hence, adding the product of the esals and kilometers performed for each truck category according to

$$\mathrm{ESALKM} = \sum_j (\mathrm{ESALS}_j \times z_j) \tag{2}$$

gives the total number of esal-kilometers performed over the year. Third, the actual level of the charge is set to cover the annual road wear and deformation and as an approximation to this, the annual status quo road maintenance cost is used[6]. The charge per esal-km is calculated according to:

$$\text{Charge per esal-km} = \text{road maintenance cost}/\mathrm{ESALKM} \tag{3}$$

Hence, the level of the charge is determined by aggregating the total number of esal-km, i.e. the total number of kilometers performed by the standard load (steps (1) and (2)), and then to divide the annual road wear and deformation cost with this number (step (3)). The result is the implied charge of one esal-km. After this, and fourthly, the charge for a particular truck is now simply determined by the product of the esals it incurs and the charge per esal, according to

$$(\text{Charge per vkt})_j = \text{Charge per esal-km} \times \mathrm{ESALS}_j \tag{4}$$

where the left-hand side is the charge for the particular truck category. In other words, the road wear cost of 1889 million SEK is divided by the total number of esal-kilometers and the result is the charge for driving a standard axle one kilometer. This procedure is repeated for each exponent. The charges are thus all designed to recover the maintenance cost.[7]

The levels of the charges are shown in Table 1. The first two columns show the power rule (exponent) with the corresponding scenario in the model. The table shows that for some truck categories, increasing the exponent means a lower charge (L3, L4, LS22, LS23, LS32, LS33, LS44) while the reverse holds for other categories

[5] An example could be the extensive timber trucking on secondary and tertiary roads, for example in the Swedish northern inlands.

[6] According to SOU 1997:35, on p. 86 of the supplement, the status quo annual maintenance cost of sealed roads is stated as approximately 1856 million SEK at 1990 prices. This is the level of maintenance that keeps the roads in a condition that is in line with the expected life span of the road, i.e. the road will be usable for the period expected in the investment plan. The road maintenance of sealed roads amounted to 1889 million SEK in 1995, and this figure determines the level of the charge. This is considered to be the best estimate of the road wear available.

[7] When referring to trucks, also other heavy vehicles like buses are included, mainly due to the availability of data issues. The higher exponents also imply that cars do not pay a charge, since the road wear would be minuscule. This is an approximation that is judged to be acceptable also in the case of the lower exponents.

Table 2
Results w.r.t. trucking; percentage change in vkt and esal-km

| | | Truck category | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | L2 | L3 | L4 | LS21 | LS22 | LS23 | LS32 | LS33 | LS34 | LS44 |
| Benchmark value | mSEK | 399.4 | 306.0 | 23.4 | 4.4 | 21.3 | 41.3 | 49.0 | 162.4 | 520.8 | 64.1 |
| SC1 | % | −8.5 | −5.3 | −1.6 | −18.9 | −10.4 | −9.1 | −8.4 | −7.3 | −8.9 | −7.9 |
| | *t*-value | 27.02 | 33.81 | 47.40 | 13.05 | 33.98 | 38.66 | 41.21 | 38.09 | 35.63 | 34.63 |
| SC2 | % | −9.6 | −5.6 | −0.4 | −20.9 | −11.7 | −10.0 | −8.5 | −6.1 | −10.5 | −8.2 |
| | *t*-value | 25.04 | 30.98 | 38.24 | 13.02 | 33.04 | 37.36 | 40.97 | 36.83 | 30.77 | 29.41 |
| SC3 | % | −9.9 | −5.5 | 1.1 | −21.4 | −11.8 | −9.8 | −7.4 | −4.6 | −11.0 | −7.7 |
| | *t*-value | 24.95 | 30.68 | 32.52 | 13.36 | 33.58 | 37.22 | 41.96 | 37.09 | 29.51 | 27.73 |
| SC4 | % | −10.3 | −5.4 | 2.4 | −21.7 | −11.8 | −9.7 | −6.4 | −3.5 | −11.4 | −7.2 |
| | *t*-value | 24.82 | 30.37 | 28.03 | 13.57 | 33.43 | 35.93 | 41.20 | 36.13 | 28.7 | 26.59 |
| SC5 | % | −10.7 | −5.2 | 3.4 | −22.1 | −11.7 | −9.6 | −5.3 | −2.8 | −11.6 | −6.8 |
| | *t*-value | 24.67 | 29.98 | 25.02 | 13.74 | 33.01 | 34.59 | 39.84 | 34.95 | 28.31 | 25.99 |

(L2, LS21, LS34)[8]. It is assumed that some truck categories are used locally, others regionally and some for long-distance transport, as explained in Johnsson (2003, Ch. 4). The main implication of this is with regard to the substitution possibilities between the different truck categories. The nested production structure and the elasticities employed are outlined in Johnsson (2003, Appendices E and F, respectively). Further details about the model are presented in Appendix A[9].

Before turning to the results, an important implication from the choice of powers has to be mentioned. Using the first power when calculating the charge, (1)–(4) above collapse into a weight-distance charge, rather than an axle-weight-distance charge. A weight-distance charge is different in some aspects from an axle-weight charge. First, considerably less information is needed to implement the charge. For example, the existing vehicle registration tax registers would probably contain the necessary information. Second, collection of the charges would probably impose a lower burden on the involved parties. The vehicles could, for example, be weighed before driving up onto a toll road, something that would be more difficult were axle-weight charges to be employed. On the other hand, we would expect some of the advantages from an axle-weight charge to be diminished were a weight-distance charge to be imposed instead. The simulations will help give an indication of the relative sizes of these offsetting effects.

## 4. Results

### 4.1. The results on road wear

Table 2 shows the changes in vehicle kilometers and esal-kilometer for each truck category in each scenario. First, in the first scenario, where the first power was used to determine the level of the charge, we see that the vehicle and esal-kilometers decreased for all truck categories, but that the decrease is different for different categories. It is the activity of the most damaging truck categories that decreases most. Secondly, we see that these results repeat themselves in the second, third, fourth and fifth scenario, only now the decrease in the activity of the most damaging truck categories is larger, and the decrease in the activity of the least damaging truck categories is smaller, than in the first scenario. We see that this effect is enhanced as the power used to design the charge increases. Moreover, the activity of the least damaging truck category within the 'local' nest, L4, even turned into positive figures in SC3–SC5.

If the figures in Table 2 are transformed into figures of road wear they result in Table 3. There we find, in the right-hand column, that road wear decreases in all scenarios, ranging from 155 to 181 million SEK. The differences between the scenarios are thus rather small, at least in relation to the overall road wear of 1889 million SEK.

The table also shows that the total esal-kilometers performed decrease to a larger extent than the vehicle kilometers performed and that this result holds for all the scenarios. However, we see that most of the effects come from the overall decrease in vehicle kilometers performed, and only to a lesser degree by shifts to less damaging truck categories. This is manifested by the relatively small differences between the decreases in esal-kilometers and the vehicle kilometers performed, ranging 'only' to an

Table 3
Effect on road wear

| | Vehicle kilometers (%) | Esal-kilometers (%) | Road wear (mSEK) |
|---|---|---|---|
| Scenario 1 | −8.0 | −8.2 | −155 |
| Scenario 2 | −8.7 | −9.2 | −174 |
| Scenario 3 | −8.6 | −9.3 | −176 |
| Scenario 4 | −8.5 | −9.5 | −179 |
| Scenario 5 | −8.4 | −9.6 | −181 |

[8] The truck categories are explained in Johnsson (2003, Appendix C). L2 = 2 axles, L3 = 3 axles, L4 = 4 axles, L21 = 2-axle truck with 1-axle trailer, etc.

[9] For information about the benchmark 1995 data set, see Johnsson (2003, Ch. 2–4).

additional 0.2% on top of the 8.0% in scenario 1, to 1.2% on top of the 8.4% in scenario 5. These figures also reveal that the shifts towards less damaging truck categories increase as the power used to design the charge increases. Finally, we see that employing a weight-distance charge in scenario 1 leads to a smaller decrease in both vehicle and esal-kilometers performed, and that the difference between these measures is smaller. The latter effect is perhaps expected, but the former is not as obvious.

Table 4 shows the effect on the government budget in all scenarios. The ex ante static effect is that another 1889 million SEK will be raised to cover road maintenance. However, after the adjustments to the charge, ex post, it turns out that only 56–63% of the 1889 million SEK will flow into the government budget.

Once again we see that the weight-distance charge of scenario 1 leads to a different result. The net positive effect on the government budget is about 120 million SEK less compared to the other scenarios. This amount is an economically relevant figure in this context since the reduction in road wear in the first scenario amounts to 155 million SEK. When choosing a weight-distance charge designed according to the first scenario over an axle-weight charge, the 120 million SEK has to be weighed against the more practical advantages of the former (as discussed above).

So far we have implicitly assumed that the charge actually was designed according to the true relation between truck characteristics and road wear. Let us relax that assumption. Table 5 provides an example in relation to the fourth power. In the second row of the table, we see the resulting changes for each truck category following the imposition of a charge designed according to the fourth power, which is most commonly assumed to be the true relation (these figures were also given in Table 2). In the first column, we find the true power, ranging from 1 to 5. If the charge was designed correctly, the results of the two rows next to 'true = 4' would hold. These are the results presented above for the fourth scenario, and we see that the 9.5% decrease in road wear equals the decrease in esal-kilometers in the fourth scenario in Table 3. But Table 5 also shows the effects on road wear when the charge is designed according to the fourth power but when the true relation is something else. The right-hand column shows that the reduction in road wear range from 8.9 to 9.6% as the true relation varies from the first to the fifth power.

Table 4
Tax payments and changes in the government budget

| | | | | | Total change |
|---|---|---|---|---|---|
| *Ex ante-static* | | | | | |
| SC1–SC5 | Costs | Government | | Revenue | |
| | Road maintenance | 0 | +1889 | Km-charge | |
| | | 0 | +1889 | | |
| *Ex post-dynamic* | | | | | +1889 |
| SC1 | Costs | Government | | Revenue | |
| | Road maintenance | −155 | +1734 | Km-charge | |
| | | | −826 | Other tax payments | |
| | | −155 | +908 | | |
| SC2 | Costs | Government | | Revenue | +1063 |
| | Road maintenance | −174 | +1715 | Km-charge | |
| | | | −697 | Other tax payments | |
| | | −174 | +1018 | | |
| SC3 | Costs | Government | | Revenue | +1192 |
| | Road maintenance | −176 | +1713 | Km-charge | |
| | | | −696 | Other tax payments | |
| | | −176 | +1017 | | +1193 |
| SC4 | Costs | Government | | Revenue | |
| | Road maintenance | −179 | +1710 | Km-charge | |
| | | | −695 | Other tax payments | |
| | | −179 | +1015 | | +1194 |
| SC5 | Costs | Government | | Revenue | |
| | Road maintenance | −181 | +1708 | Km-charge | |
| | | | −696 | Other tax payments | |
| | | −181 | +1012 | | +1193 |

Table 5
Charge designed according to the 4th power and true power varies between 1 and 5

| | | L2 | L3 | L4 | LS21 | LS22 | LS23 | LS32 | LS33 | LS34 | LS44 | Total | % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | % | −10.3 | −5.4 | 2.4 | −21.7 | −11.8 | −9.7 | −6.4 | −3.5 | −11.4 | −7.2 | | |
| *true = 1* | Esal-km[a] | 1 098.9 | 672.8 | 32.2 | 23.4 | 170.6 | 266.1 | 561.7 | 1 207.7 | 3 478.4 | 292.5 | 7 804.3 | |
| | Change | −112.9 | −36.0 | 0.8 | −5.1 | −20.1 | −25.8 | −35.8 | −42.3 | −396.2 | −21.0 | −694.5 | −8.9 |
| *true = 2* | Esal-km[a] | 1 298.4 | 742.6 | 28.2 | 28.0 | 194.7 | 295.4 | 585.9 | 1 154.7 | 4 264.4 | 334.9 | 8 927.4 | |
| | Change | −133.4 | −39.8 | 0.7 | −6.1 | −22.9 | −28.7 | −37.4 | −40.5 | −485.7 | −24.0 | −817.8 | −9.2 |
| *true = 3* | Esal-km[a] | 1 624.1 | 864.8 | 25.0 | 34.8 | 229.5 | 341.5 | 632.7 | 1 189.0 | 5 371.1 | 398.1 | 10 710.5 | |
| | Change | −166.9 | −46.3 | 0.6 | −7.6 | −27.0 | −33.1 | −40.3 | −41.7 | −611.8 | −28.6 | −1 002.7 | −9.4 |
| *true = 4* | Esal-km[a] | 2 117.1 | 1 047.9 | 22.2 | 44.3 | 278.2 | 409.4 | 705.7 | 1 310.6 | 6 882.8 | 487.5 | 13 305.7 | |
| | Change | −217.6 | −56.1 | 0.5 | −9.6 | −32.8 | −39.7 | −45.0 | −46.0 | −783.9 | −35.0 | −1 265.1 | −9.5 |
| *true = 5* | Esal-km[a] | 2 836.7 | 1 304.8 | 20.0 | 57.6 | 345.6 | 506.7 | 810.5 | 1 526.4 | 8 914.2 | 610.3 | 16 932.8 | |
| | Change | −291.5 | −69.9 | 0.5 | −12.5 | −40.7 | −49.2 | −51.7 | −53.5 | −1 015.3 | −43.8 | −1 627.6 | −9.6 |

[a] Millions.

If the same kind of computation is performed for all the five scenarios, the results could be displayed in a matrix, as in Table 6. In the table, the columns represent the power relation chosen when the charge was designed and the rows the true relation. Again, focusing for example on the column where the fourth power relation was used for the charge, we see that the deviation from the true relation resulted in a deviation of −0.6, −0.3, −0.1 and +0.1% of annual road wear costs. These figures could also be found in the right-hand column in Table 5 by subtracting −8.9, −9.2, −9.4 and −9.6 from the true fourth power result of −9.5. Making the same computations for all the other scenarios shows that the deviation from the optimal change in road wear costs ranges from −0.8 to +0.2% of annual road wear costs. A positive figure means actual road wear is reduced more than the optimal, a negative that actual road wear is reduced less than the optimal. Hence, if the true relation between truck characteristics and road wear lies somewhere between the first and the fifth power, the deviation from the optimal incurred by designing the charge according to a false power ranges between −15.1 and 3.8 million SEK, as long as the charge is designed according to one of the five powers.

### 4.2. The results of the sensitivity analysis

The aim of the sensitivity analysis is to try to see how robust the results are with regard to certain assumptions about parameter values, especially the elasticities. The procedure, a so-called unconditional systematic sensitivity analysis, follows Harrison and Vinod (1992). The idea is that the model is solved over and over again while some key parameters are simultaneously perturbed, very much like a Monte Carlo simulation. The key elasticities in the study are the substitution elasticities within the trucking nests and between the trucking nests. These are shown in Table 7[10].

Table 6
Cost of being wrong, percentage of annual road wear costs

| True exponent | Charge designed according to exponent | | | | |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 |
| 1 | – | −0.2 | −0.3 | −0.6 | −0.8 |
| 2 | 0.1 | – | −0.1 | −0.3 | −0.5 |
| 3 | 0.1 | 0.1 | – | −0.1 | −0.2 |
| 4 | 0.2 | 0.2 | 0.1 | – | −0.1 |
| 5 | 0.2 | 0.2 | 0.2 | 0.1 | – |

A positive figure means actual road wear is reduced more than the optimal, a negative means that actual road wear is reduced less than the optimal.

The parameter values are perturbed simultaneously and the model is then solved 1000 times[11]. The resulting *t*-values are shown in Table 2 above. The results do overall appear to be statistically significant at a 5% level of statistical significance[12]. Hence, the results seem to be robust with regard to the key parameters of the study.

## 5. Concluding remarks

In this study, an axle-weight-distance related kilometer charge has been differentiated for 10 different truck categories according to their contribution to road wear and deformation. The AASHO Fourth Power Rule, set to cover the annual road wear and maintenance costs in Sweden, determines the money cost of this contribution on the margin. The charge has also been designed by varying the power, from the first through the fifth power. The different charges have then been simulated in a CGE model.

[10] Finding estimates for these elasticities turned out to be almost impossible, so rough guesstimates have had to be made. However, the guesstimates were guided by studying several sources, including the changes that appeared when Sweden abolished the previous kilometer charge in 1993. Although not very accurate statistically, they provided some guidance. The uncertainty of the figures will be handled within the systematic sensitivity analysis. For more on this, see Johnsson (2003, Appendix F).

[11] Following Harrison and Kriström (1997) and Hill (1998), the sample size, i.e. the number of times the model is solved is set to 1000. For more on this, see Harrison et al. (1993).

[12] Note that not all distributions are assumed to be normal, so that the critical *t*-values are valid only asymptotically.

Table 7
Some key elasticities

| Elasticity of substitution | Point estimate | Range | Distribution |
|---|---|---|---|
| Between input of 'local' trucks | 0.2 | (0.0, 0.4) | Uniform |
| Between input of 'regional' trucks | 0.4 | (0.0, 0.8) | Uniform |
| Between input of 'long-distance' trucks | 0.6 | (0.0, 1.2) | Uniform |
| Between the nests | 0.25 | (0.0, 0.5) | Uniform |

The results are similar in all scenarios except when the first power is employed. Studying the results in detail, we see that we could expect a decrease in activity in the most damaging truck categories according to all scenarios. Also, when the higher powers are used to design the charges, the charge actually might lead to significant increases in the activity of the least damaging truck category (assumed to be used only locally).

The decrease in overall road wear ranges from 155 when the first power is used to 174–181 million SEK when the higher powers are used. This could be compared to the total road wear cost of 1889 million SEK that was used to determine the level of the charges. It is notable that the use of the first power leads to less reduction in road wear.

Most of the decrease in road wear in the model appears to be a result of the decrease in the general trucking activity and only to a lesser extent a result of shifts towards less damaging truck categories. The decrease in the overall number of vehicle kilometers performed ranges between 8.0% when the first power is used and 8.4–8.7% when the higher powers are used. Moreover, the 'extra' decrease in the overall number of esal-kilometers performed increases as a higher power is used to design the charge. This is not really the case when the first power is used, as expected.

The effect on the government budget varies with the choice between a first power and the higher powers. In the first case, only 56% of the tax revenue expected to be raised, based on a static calculation, was actually raised in the model. In the other cases, about 63% was raised. The difference between 63 and 56% amounts to about 120 million SEK. If this figure is compared to the reduced road wear costs of 155 million SEK of the first case, we see that the magnitude is significant. Furthermore, it is indeed notable that as little as between 56 and 63% of 1889 million SEK actually flowed into the government's accounts after the adjustment to the newly imposed charges.

These results were based on the assumption that the people designing the charge, thereby choosing a power rule, made the right choice. By studying the effects of designing the charge according to one power relation, while the true one was another of the five at hand, the model results told us that the cost of being wrong appears to be modest. Choosing the wrong power leads to a deviation from the effects when one was right of between $-0.8$ and $+0.2\%$ of the annual road wear costs. It appears being wrong about the power is somewhat worse if the true relation is the first power, but the cost of being wrong is rather modest in comparison to annual road wear costs.

The difference between the use of a first power compared to the others is that designing the charge according to the first power amounts to a weight-distance charge rather than an axle-weight-distance. Thus, the results reveal that there are implicit costs of implementing a weight-distance charge. Even the cost of being wrong was slightly higher in this case, although modest. Such implicit costs then have to be weighed against other practical advantages of the weight-distance charge, for example that less information is needed and that it imposes less of a burden to collect the charges. However, the present model provides no answer to such judgements.

The results presented here appear to be robust with regard to the choice of some key parameters. However, it is perhaps also appropriate to raise some uncertainties regarding these results. The results are of course highly dependent on the design of the charge, the choice of model used for the simulations, the model structure itself, etc. A degree of caution is therefore called for when inferring the consequences of these results in the real world. Finally, a few words about future work. Since the model simulation of this study would seem to indicate that the choice of power is of only minor importance, except in the case of the first power, I suggest that more effort needs to be put into (i) finding a monetary measure of road wear, (ii) finding a charging technology that satisfies relevant minimum cost and maximum convenience criteria, both for the trucking business and the collection of the charges, and (iii) finding ways to compensate the trucking businesses financially for their increased costs, for example by lowering some other tax they are forced to pay today.

## Appendix A. The model

The model is a static, small open economy, computable general equilibrium (CGE) model in the Shoven and Whalley (1972) tradition, calibrated to fit the Swedish input–output matrices of 1995.

Based on neo-classical microeconomic theory, there is a number of profit maximizing firms producing commodities using intermediate inputs (i.e. other commodities as well as some of the same commodity) as well as labour and capital inputs. The production exhibits constant returns to scale and the output is sold on so-called 'perfectly' competitive commodity markets. This can be described as

$$Y_j = G_{ji}(I_{ji}, VA_j) \quad \text{(A1)}$$

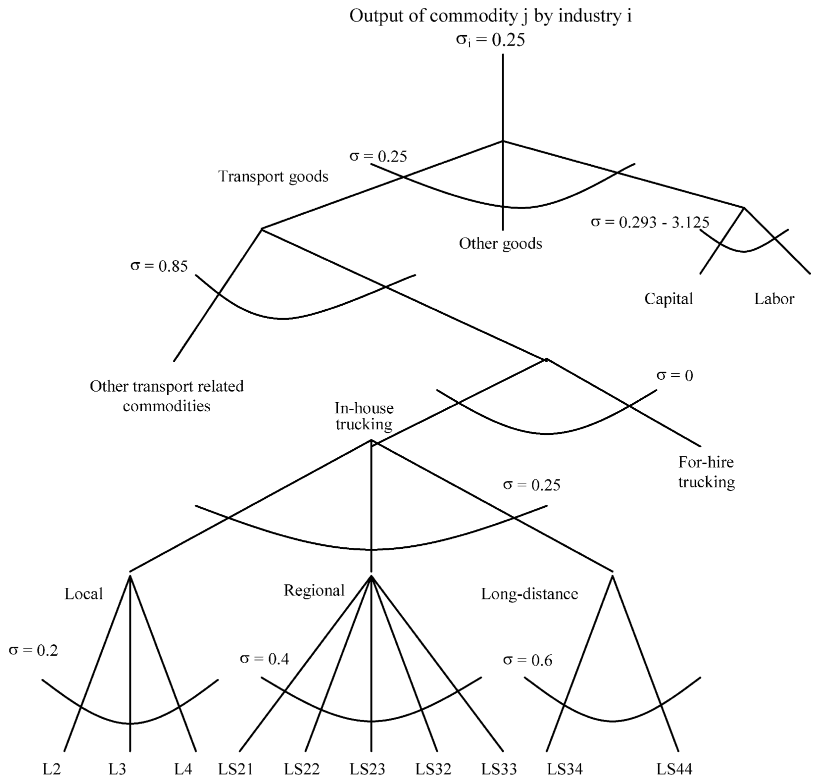


Fig. A1.

where the $j$th industry, $Y$, produces one or more commodities, $G_i$, using intermediate inputs, $I_i$, and value added, VA. The subindices $j$ and $i$ denote an industry and a commodity, respectively. The value added consists of capital and labour input according to

$$VA_j = VA_j(K_j, L_j) \tag{A2}$$

where $K$ and $L$ denote capital and labour inputs, respectively. The production functions are Leontief, Cobb-Douglas or CES. The output of each commodity is designated to the export or the domestic market. Together with the imported commodities the output designated for the domestic market form the domestic supply. The imports are modelled according to the Armington (1969) assumption, meaning that imported and domestic commodities are not perfect substitutes, but rather only close substitutes. For symmetry reasons the same applies for the exports.

The labour market is modelled as a competitive market that is cleared by adjustment of the real wage rate. The labour supply function is calibrated according to Ballard (1999), whereby the labour supply function is calibrated to the desired labour supply elasticity. As Ballard points out, the labour supply elasticity determines the elasticity of substitution between commodities and leisure in the utility function. Or, conversely, by choosing the latter, one indirectly determines the former, something often seems to have been overlooked in CGE modelling. Ballard shows that this is of great importance, among other things for the welfare results.[13]

The domestic supply is either consumed as intermediate input, as an investment commodity, or consumed by the government or by a representative consumer. The final demand of the representative consumer is represented according to a utility function

$$U = U(G, l) \tag{A3}$$

where the consumer derives utility from consuming commodities, $G$, and leisure, $l$. The consumer finances the purchases by selling their endowments of capital and labour to the producers in the labour and capital markets. In addition, the consumer also receives transfers from the government and the consumer carries out the investments. The government finances its consumption by collecting taxes from producers and the consumer. The model is closed by balancing the current account, keeping it at the benchmark level by adjusting the real exchange rate.

The nested production structure is given by Fig. A1, where also the point estimates of the elasticities are shown. For more about the elasticities, see Johnsson (2003, Appendix F).

[13] See Johnsson (2003, Appendix B) for a fuller description of Ballard's point in relation to the current model.

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