Indirect energy associated with Swedish road transport

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Typically when transport systems are considered from an energy or environmental perspective it is primarily the energy use associated with the propulsion of vehicles that is addressed. There are however other significant energy categories associated with transport systems, labelled as indirect energy – construction, operation, maintenance and demolition of infrastructure; manufacturing, service and scrapping of vehicles; and fuel production.
In this paper the indirect energy is calculated to slightly more than 45% of the total energy use in the Swedish road transport sector. In detail, infrastructural energy stands for approximately 22%, vehicular energy at least 14%, and fuel production about 9% of the total energy use.
In conclusion, the insight into the significance of the indirect transport energy should have implications on transport policy, for example, the design of means of control to reduce energy use and environmental impact. Four scenarios involving energy-saving measures are tested, and even though direct energy use remains the single largest item, policy-makers concerned with reducing road sector CO_2-emissions cannot focus exclusively on the consumption of petrol and diesel for propulsion, but should also give heed to the energy use associated with infrastructure and vehicles.

Keywords: energy, environment, roads, Sweden, transport

1. Introduction

When the transport systems are considered from an energy and environmental perspective, the energy use associated with the consumption of fuels used for the propulsion of vehicles generally receives the greatest amount of attention. There are however also a number of other indirect energy-using phases in the lifecycle of transport systems, e.g. construction and maintenance of roads, manufacturing and service of vehicles, and production and distribution of petrol and diesel. The overall purpose of this paper is to investigate the significance of indirect energy, in comparison with total energy use in the Swedish road transport sector.

This paper summarises a pilot study (Jonsson, 2005) that systemises and quantifies the indirect energy use associated with transportation. The source data used emanates from some thirty previous transport energy studies: Berry and Fels (1973), Boyce et al. (1981), Cordi (1979), DeLeuw, Cather and Company (1975), Elbeck (1974), Eriksson et al. (1995), Erlbaum (1981), Fels (1975), Graedel and Allenby (1998), Heiberg (1992), Hille (1991), Hiorth (1980), Hirst (1972), Holm et al. (1980), Hudson et al. (1981), Irwin (1978), Kalenoja (1996), Levinson et al. (1984), Mroueh et al. (2000), Park et al. (2003), Singh (1987), Smith (1980), Smylie (1975), Stammer and Stodolsky (1995), Stripple (1995), Svensson and Eklund (2003) and Talaga et al. (1983). All source data are presented in their entirety in Jonsson 2005. Some data are used in section 2 to illustrate the distribution of the primary data and the size differences among the various indirect energy items. Combined with Swedish statistics of transport, infrastructure, vehicles and fuel consumption, a selection of average data is used to create a model of the total energy use associated with Swedish road transport (section 3). Henceforth in this paper, when average data from several of the above studies is used, this is referred to as "processed data in Jonsson 2005". Of course, when singular data is used, the original source is reported.

The compilation and systematisation of the different energy items can in itself be considered policy relevant, since it by elucidating on the share of the total quantity of energy considered indirect, might indicate areas with potential for improved efficiency. Moreover, some hypothetical scenarios involving certain energy-saving measures are tested (in section 4) resulting in coarse estimations of the impact of different energy reducing strategies in the road transport sector.

2. The indirect energy associated with road transport in general

The indirect energy use associated with road transport can be divided into the following items:

- Construction, operation, maintenance, and demolition of infrastructure;
- manufacturing, service, and scrapping of vehicles; and
- fuel production.

In the following sections the different indirect energy items are reviewed and discussed, as are possible connections between them. Also, size orders are exemplified by means of selected data.

2.1 Construction of infrastructure

The energy use associated with the construction of a typical stretch of road is primarily determined by its length, since it depends largely on the volumes of material to be produced, transported, prepared and put in place. Other infrastructure characteristics, such as width, type, and choice of material, also influence energy use, as do geographical conditions determining the extent of ground preparation and demolition work required. In this context the occurrence of tunnels and bridges is of particular significance.

The construction of infrastructure is largely an endeavour of mass hauling, as a significant part of the energy use is related to the relocation of earth, stone and construction material. International energy statistics for construction of infrastructure however varies greatly. Local geography is of course an important factor, as are type and amount of material used. Estimated useful life also varies with different studies. In order to allow relevant comparisons to be made, energy use in construction should be distributed equally over a number of years. If infrastructure is expected to remain functional for all eternity, the yearly impact of construction would be negligible. If measurement is done only during the time of actual construction, energy use will be disproportionately inflated in this period. The life expectancy estimated in the calculations should be sensitive to the fact that some components wear out relatively fast while others are more durable. In the majority of energy studies previously referred to this generally corresponds to so-called economic lifetime.

To some extent the energy use associated with construction is determined already in the planning stage. Although a straight route involves a shorter total infrastructural length, it may on the other hand require additional arrangements to breach mountains and bridge valleys and streams. Bridges and tunnels necessitate the use of a greater variety of material types of differing energy intensity. The total energy spent building an ordinary twelve-meter concrete bridge is estimated to approximately 1600 GJ (Stammer and Stodolsky, 1995; Graedel and Allenby, 1998), whereas the construction of a 500-meter suspension bridge is estimated to approximately 100 times more energy (Hiorth, 1980).

In the early stages of road construction, groundwork such as removal of the overburden and excavation of rock and earth dominate in terms of energy use. Surface preparations require approximately 2,500 GJ/km when considering an average public main road (processed data in Jonsson (2005)). Thereafter follows the construction of the road’s pavement structure, which involves both the production of materials as well as the construction of base course (the expression ‘telford base’ is also used in some sources), sub-base and surface course, each layer requiring between 2,500 and 4,000 GJ/km (processed data in Jonsson (2005)). The surface course is repaired and replaced regularly (which however counts as maintenance).

Apart from the road’s main constituent parts, there are also other additional items associated with infrastructure construction, e.g. road signs, which for a four-lane freeway in a Danish study (Holm et al., 1980) is amounted to approximately 85 GJ/km. On the same road, major interventions such as divided level crossings, access ramps and service areas (divided over the entire stretch) could add up to as much as 7,600 GJ/km.

Total energy use related to road construction varies substantially depending on road type and external circumstances. The data shows a spread from about 10,000 GJ/km – for smaller European public roads – to about 1,500,000 GJ/km – for American freeways that are elevated or run through tunnels.

Regardless of type, it must be concluded that the indirect energy use associated with the construction of infrastructure is considerable. There is approximately 200,000,000 TJ embedded in the global road systems (Graedel and Allenby, 1998), which corresponds roughly to half of the global annual energy use.

2.2 Infrastructure operation

The operation phase is rather loosely defined in the literature. Often everything except construction and demolition of infrastructure is included here. In this paper however, ‘infrastructure operation’ refers to the supporting functions that render possible or facilitate the use of the infrastructure, i.e. excluding the propulsion of vehicles and maintenance requiring physical interventions. Operation of a road system typically includes for example traffic lights, lighting and cleaning activities, e.g. snow-clearance, sand spreading, salting, street-sweeping, clearing vegetation alongside the road, cleaning of safety posts and road signs, placing out and removal of road markers and clearing of ditches.

The need for such supporting functions can entail that lightly trafficked areas will have a relatively high operation energy use per produced person-km, while more heavily trafficked stretches benefit from scale effects. On the other hand, intensive use may call for additional functions, for example to maintain safety levels or to manage congestion. These supporting functions are however generally independent of transport volumes – either they are on or they are off, e.g. road lighting, which generally is a significant operation item. In one study the operation phase is estimated to fifty percent of the total lifecycle energy use of an ordinary, illuminated thirteen-meter road with traffic control, approximately 300 GJ/km/year (Stripple, 1995, in Svensson and Eklund (2003)). In general, it is however only a fraction of the roads that are illuminated, primarily in urban areas and in conjunction with bridges and exits. For the remaining majority, operation energy only amounts to about five percent of the total, which translates to about 11 GJ/km/year (ibid.).

The data gathered on road operation suggests a typical energy use of between 10 and 30 GJ/km/year in average (processed data in Jonsson (2005)).

2.3 Infrastructure maintenance

Regardless of use, maintenance is required due to corrosion, erosion and displacements like for example frost heaving. The need for this kind of maintenance is unrelated to transport volumes. Other maintenance depends on wear and tear related to use. Energy spent on maintenance can thus be divided into a fixed part and a variable part. An ordinary thirteen-meter road with a traffic intensity of 2,000 vehicles per mean annual day and a life expectancy of forty years requires about five replacements of the surface course, while an intensity of 9,000 vehicles calls for eight replacements (Cordi, 1979).

The energy associated with maintenance of Swedish public roads has in one study been estimated to about 70-80 GJ/km/year (depending on type of surface course) (Stripple, 1995; Svensson and Eklund, 2003). Another Swedish estimate that also includes the manufacturing and service of machinery to manage maintenance however indicates energy use four to five times as large (Cordi, 1979). This estimation does not appear unrealistic in comparison with the results of some international studies where running repairs have been included in a life cycle perspective, e.g. surface coating (gravel, oil gravel, asphalt, etc.), diesel for working machines, painting of road markings and median line, and additional filling material such as gravel and concrete (processed data in Jonsson (2005)).

2.4 Demolition of Infrastructure

When infrastructure is torn down energy is spent on the mechanical dismantling, transport and subsequent management of demolition waste. To the extent that transport infrastructure ever actually is demolished it constitutes a relatively small, but varying, energy item (there is however a potential for recycling of materials that in some cases can result in a positive energy account). Here the level of ambition with which the interventions are made is crucial. For example the removal of surface coating (light demolition work) in connection with maintenance is not particularly energy demanding. In an American example, the energy cost for light demolition work on a city road is estimated to about 8 GJ/km. This is compared to the estimated 330 GJ/km spent on heavy demolition work in connection with reconstruction of a major arterial (Levinson et al., 1984). Another example estimates an energy use of 1,446 GJ/km for the complete demolition of a Korean freeway (Park et al., 2003).

There are few examples of infrastructure demolition where there has been both a complete restoration and collection of data on energy use. The demolition of infrastructure is not further included in the calculations of this paper. Since roads rarely are torn down, the energy spent on demolition is considered to be negligible. Furthermore it can in some cases be assumed that the energy that actually is spent on demolition already is included in the calculations together with the energy use associated with maintenance or the construction of new roads (i.e. when old roads are reconstructed).

2.5 Manufacturing of vehicles

This item includes the whole chain of production from raw material extraction (e.g. mining) through production of materials and components to assembly in factories. Within a well-defined system – in this case, Swedish road transport – energy use is determined primarily by the number of produced vehicles and the specific vehicle types and production materials involved. Although some energy items are fixed, for example heating of factories, the lion’s share varies with production volumes.

In order to be able to compare the manufacture of different types of vehicles in terms of energy use in a relevant manner, expected working life must be included. A normal approximation for automobiles is a working life expectancy of fifteen years. Trucks and buses can be expected to stay in service 10-15 years, depending on how they are used. For example, regional buses last longer than city buses.

Studies place energy use associated with the manufacture of automobiles in the order of 50-200 GJ/vehicle. The variability depends partly on differing vehicle weights, partly on the method used (input-output, life cycle analysis or process analysis), and partly on the delimitations made considering the manufacturing chain (processed data in Jonsson (2005)).

The corresponding values for buses and trucks appear to be about a factor 10 higher, 500-2,000 GJ/vehicle (processed data in Jonsson (2005)). As far as trucks are concerned, large variations are to expect since some weigh only a few tonnes, when others can have a total weight of more than 20 tonnes. A 3.5 metric ton commercial vehicle requires approximately 200 GJ of manufacturing energy, whereas a 23 metric ton tank truck (including trailer and tank) is estimated to about 1,100 GJ (Cordi, 1979).

To sum up, the studies implicate raw material extraction as the main energy item in the entire manufacture process (processed data in Jonsson (2005)). It is also the energy item over which the vehicle manufacturers have the least control.

2.6 Service of vehicles

This refers to the energy required for the production of spare parts (including tires) and lubricating oil, as well as the energy used during the actual servicing. The energy use associated with service of the vehicle population is primarily determined by the amount of wear resulting from use. On the other hand, material in vehicles will age and deteriorate whether they are used or not. Time, weather and wind might in some cases constitute a significant constant factor.

It is difficult to pertinently estimate the energy use related to the service of vehicles, i.e. consumption of spare parts, tires and lubricating oil. As mentioned, the level of use is pivotal. Heavier use means more wear, which calls for more frequent service. Regular service contributes to extending the life time of vehicles and trailers, but in some circumstances it can be more profitable to limit the amount of service on commercial, capital-intensive vehicles and trailers, e.g. trucks, since they cost money even when they are standing still. In these cases it might be more cost-effective to keep the vehicles in use until they are in substandard condition, and then sell them off to an entrepreneur with lower standards, or simply scrap the vehicle. When it comes to private vehicles however, there are different philosophies of priority. Some choose to invest in extensive preventative service in order to extend lifetime or maintain quality and trade-in value, while others prefer to change vehicles in an earlier stage. Natural variations in climate and other environmental factors of course also affect the need for service.

The Swedish study of Cordi (1979) estimates the yearly energy use related to the service of cars (excluding tires and lubricating oil) to 0.93-2.5 GJ/vehicle/year. When lubricating oil and tires are included together with the other spare parts, the number turns out to be about 1.6-4.0 GJ/vehicle/year. A few other international studies where input-output analyses were made, however, suggest that the service-related energy use exceeds 10 GJ/vehicle/year.

Cordi (1979) estimates the energy use related to the service of trucks to about 3-30 GJ/vehicle/year, depending on the truck's weight (ranging from 3.5 to 23 tonnes).

The energy use related to the service of buses is however larger. In some American studies, bus service energy is estimated to somewhere between 100 and 400 GJ/year (processed data in Jonsson (2005)). The variance is partly explained by differences in estimated serviceable life. However, the dominant cause of the variance and the quantity (compared with cars and truck) is likely how service-related energy is defined. Stationary heating of buses can be included or excluded. For Swedish conditions, Cordi (1979) estimates stationary heating to about 78 GJ/vehicle/year. A similar Norwegian estimation by Heiberg (1992) turns out to between 46-87 GJ/vehicle/year. Stationary heating of buses is apparently a significant issue in countries with a colder climate.

2.7 Scrapping of vehicles

In terms of energy use, scrapping of vehicles refers to dismantling and to a limited extent transport of materials. From a lifecycle perspective, scrapping can entail a surplus of energy. When the average truck is scrapped, the energy spent on waste product management is in one study estimated to 13 GJ. If there is a 95% recycling of iron, however, approximately 66 GJ is made. For a passenger car the corresponding values are about 3 GJ for waste product management and a potential realisation of approximately 8 GJ in connection with recycling of iron (Eriksson et al., 1995).

2.8 Fuel production

This process includes extraction from the primary energy source, transportation of raw material, conversion into fuel and distribution to the end user. As far as fossil fuels are concerned, production includes for example drilling for crude oil, refining, and the construction and operation of petroleum refineries. Distribution of refined fossil fuels, from refineries to consumers, does not however appear to constitute a large share of this category of indirect energy. Cordi (1979) estimates that the distribution of petrol, diesel and aviation fuel consumes approximately 0.5% of the energy value of the transported fuels. In the case of petrol however there is also an estimated 1% wastage due to evaporation and leakage in connection with distribution.

An average add-on to the energy value of fuels, i.e. indirect energy use associated with production, is approximately 12-14% for diesel, and about 18% for petrol (average estimations compiled in Kalenoja (1996) and Eriksson et al. (1995)).

3. Annual energy use associated with Swedish road transport

In this section the energy data discussed in section 2 is combined with Swedish statistics for roads, vehicles and fuel consumption to calculate the energy use, on a yearly basis, of road transport in Sweden. The energy items are structured according to the previously described classifications: construction, operation, and maintenance of infrastructure; manufacturing, service, and scrapping of vehicles; and fuels in terms of production and in this compilation also direct energy use for propulsion.

The calculations include freeways, ordinary public roads, streets and private roads, cars, buses, trucks and other vehicles (e.g. trailers and working machines), and fuel, primarily petrol and diesel. The calculation sheet with the total estimated energy use is found at the end of this chapter (section 3.4). All statistics used are reported in this chapter, as are the assumptions that form the basis of the calculations.

Making an annual report for fuels is not very complicated. It is simply a question of gauging use during a recent year. When it comes to vehicles, averaging adjustments are required. In essence, manufacturing energy is spread out over the objects' life time, by estimation 10-20 years, in order to make valid comparisons possible. As for infrastructure, which remains for 20-100 years or possibly even longer, it gets more complicated. Here, two different approaches can be identified. One is to study the roads constructed during one year (or an average of several years), and by means of material specifications calculate energy use related to construction. This method has not been feasible in this study. The other is to examine the existing infrastructure stock, estimate the total amount of energy spent on its construction based on collected average data, and then divide this over expected economic lifetimes. This has been the method of choice in this paper.

3.1 Infrastructure

The Swedish road transport grid consists of approximately 420,000 km streets, roads, freeways, etc., as specified in table 1.

Table 1. The Swedish road grid

	Lanes	Length [km]
Municipal streets	1+1	37,000
Private roads (including forest motor roads)	~1	284,000
Freeways	2+2	1,579
Arterials [1]	2+2	60
Arterials [2]	2+1	300
Four-lane roads	2+2	228
Ordinary public roads [1]	2+2	40
Ordinary public roads [2]	2+1	439
Ordinary public roads [3]	1+1	95,555

Source: Swedish Road Administration (2004)

The estimation of annual energy use associated with the construction of infrastructure is made with consideration of the number of lanes divided over expected lifetime. A few extreme values in the base data compilation in Jonsson (2005) that comprise major road projects in urban areas have not been included in the calculation of mean values. City roads and streets are approximated to public roads. Arterials are approximated to freeways (in some cases the construction of an arterial can be considerably more energy- demanding since it runs through an urban area, whereas others are more similar to ordinary freeways or public roads in this regard). The average for freeways and arterials comes out to 55,700 GJ/lane-km. For ordinary public roads, city roads and streets the average is 9,650 GJ/lane-km. Private roads have been approximated to one-lane public roads without surface course, which corresponds to 2,775 GJ/km, while forest motor roads (approximately 150,000 km) have been approximated to one-lane public roads with neither surface course nor sub-base, i.e. only base course, corresponding to 1,475 GJ/km (processed data in Jonsson (2005)). The roads' estimated lifetimes vary among the different sources between 20-50 years. Here an average economic lifetime of 40 years is used consistently (which also is the estimate used in many studies).

As far as operation is concerned, freeways and arterials have approximately the same energy needs, about 34 GJ/lane-km/year. Energy use associated with the operation of public roads is estimated to 17.5 GJ/lane-km/year. For city streets the estimate is 14.5 GJ/lane-km/year. The operation of private roads that are not forest motor roads consists of snow clearing and other surface treatment, which is estimated to 5 GJ/km/year (processed data in Jonsson (2005)).

The calculation for maintenance is based on processed data in Jonsson 2005 (which however primarily includes results from Swedish studies). This turns out to be 175 GJ/lane-km/year for freeways, 36 GJ/lane-km/year for public roads, and 64 GJ/lane-km/year for city streets. Maintenance of private roads is assumed to consist mainly of light surface treatment and strengthening of the base course (estimated to 20 GJ/km/year) for those that receive state subsidies, which corresponds to approximately 74,000 km (National Swedish Association of Private Roads, 2004).

In summation it can be concluded that construction is responsible for a considerable share of the energy use associated with road infrastructure, which is illustrated in figure 1 (energy quantities are presented in table 4).

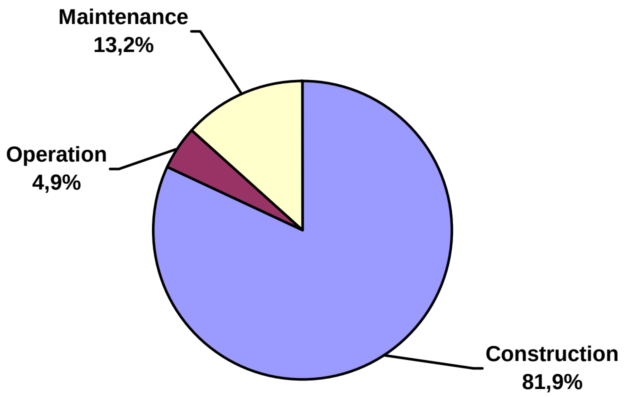

Figure 1. Shares of indirect energy associated with Swedish road infrastructure.

3.2 Vehicles

The Swedish vehicle population is assumed according to table 2 (rounded averages 1998-2001; Statistics Sweden 2004, Swedish Institute for Transport and Communication Analysis 2004, Bil Sweden 2003).

Table 2. Vehicles in Sweden (trailers and motorcycles excluded)

	Cars	Buses	Trucks	Tractors etc.
In traffic	3,948,000	14,100	374,200	325,700
Temporarily deregistered	765,000	4,500	113,400	72,100
Registrations	316,800	1,200	35,500	4,500
Deregistered	199,200	900	13,500	1,300

3.2.1 Manufacturing

The calculation for cars is based on processed data in Jonsson 2005, with a weighting regarding vehicle weight. The average weight of a Swedish car is about 1,400 kg (BIL Sweden, 2003). The average energy use associated with the manufacture of cars has ultimately been estimated to 110 GJ/vehicle. Expected lifetime is assumed to be 15 years. Temporarily deregistered vehicles are also included in the calculation.

Energy use associated with the manufacture of buses has, based on processed data in Jonsson 2005, been estimated to 1,013 GJ/vehicle. Expected working life is assumed to be 15 years. Temporarily deregistered buses are also included in the calculation.

With trucks simple average figures can not be used since the population is unevenly distributed over different weight categories. A majority are classified as light trucks (i.e. with a total weight of less than 3.5 tonnes), but Sweden also has a relatively large share of really heavy trucks (with total weights exceeding 24 tonnes). Below rounded average numbers for the years 1999-2003 (processed data from BIL Sweden, 2003) are reported together with the estimated average energy use associated with manufacturing (based on processed data in Jonsson (2005)). Table 3 also contains data on service energy use (ibid.).

Table 3. Trucks in Sweden distributed over weight categories

Total weight tonnes	Quantity	Manufacturing energy GJ/truck	Service energy GJ/truck/year
< 3,5	271,900	180	3.54
3,5-7,0	36,100	240	4.86
7,0-12	11,100	295	10.15
12-16	5,800	370	15.26
16-24	17,900	500	24.00
> 24	31,400	840	26.00
> 24 (tank)	2,030	1,100	28.18
Average residual item*	111,370	267	9.72

* This balancing item adjusts differences in statistics from various sources, and represents mostly temporarily deregistered trucks not arranged in weight categories in available statistics. The associated energy figures in the table have been calculated based on the assumption that the weight distribution in this item corresponds with the registered truck fleet in Sweden.

Table 3 constitutes the basis for the truck calculations. The average working lifetime of trucks is estimated to 15 years.

There is also an item on the calculation sheet designated to other vehicles, where relatively rough assumptions have been made. This item includes for example tractors, working machines and trailers. There are about 400,000 working machines and tractors in Sweden, from very light ones to heavy dump trucks and mining machinery. Similarly, the population of trailers is very diverse. Approximately 500,000 of the Swedish trailers have a maximum capacity of 1,000 kg, i.e. small trailers and caravans. In addition to these there are about 50,000 trailers for heavy cargo, a couple of thousand of which can handle loads of more than 30 tonnes. This item further is assumed to include somewhere in the neighbourhood of 200,000 motorcycles (Statistics Sweden, 2004).

It is in this context not possible to make a detailed calculation of this item. The resulting approximation is tantamount to 1,000,000 half automobiles (i.e. 55 GJ per trailer or vehicle) with expected serviceable lives of 20 years. This is considered a low rough estimate rather than an overestimation.

3.2.2 Service

The calculation for cars is based on weighted (regarding vehicle weight) average data (processed in Jonsson (2005)), and turns out to 4.67 GJ/vehicle/year. The result on the calculation sheet does not take temporarily deregistered vehicles into account, as they generally are subject to minimal service.

Also the calculation for buses is based on average data (processed in Jonsson (2005)), which gives 183 GJ/bus/year. Stationary heating is included in that figure, which explains the great difference between cars and buses. Temporarily deregistered vehicles are however not included in the calculation.

The calculation for trucks is based on data grouped according to total weight in table 3. The table's residual item (which is assumed to mainly represent temporarily deregistered trucks) is left out of the result on the calculation sheet.

As for the service of the category 'other vehicles', like in previous sections, a rough approximation is made based on the maintenance of one half automobile with an adjusted lifetime of 20 years, which corresponds to 3.1 GJ/year for approximately 1,000,000 miscellaneous trailers and vehicles.

3.2.3 Scrapping

Of 199 200 deregistered vehicles (according to table 2), an average of 191,385 (about 96%) were scrapped – a large share of the deregistered cars in Sweden have been scrapped during the recent years due to higher scrapping premiums. As for other vehicle types it is assumed that a share of 80% of the deregistered vehicles are scrapped.

The calculations for scrapping are based on processed data in Jonsson (2005) and Swedish primary data in table 2. Buses and trucks are considered equivalent. As before, every object in the item ‘other’ corresponds to one half passenger car.

Associated with scrapping, a 95% recycling of iron is assumed, which entail a surplus of energy in a life-cycle perspective. This means that vehicle scrapping in table 4, mirroring annual energy use, appears as negative figures.

3.2.4 Summary road vehicles

Energy use size orders are shown in table 4. In terms of shares, it can be concluded that the energy use associated with vehicles on the Swedish roads is dominated by the item car:

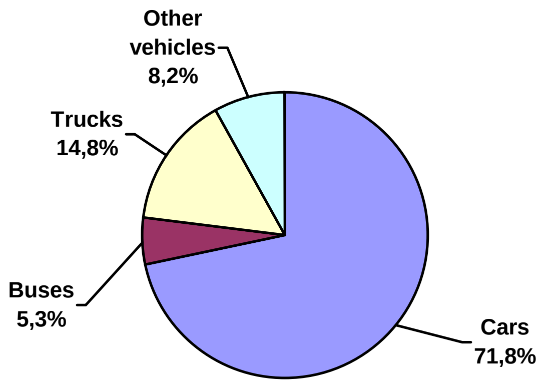

Figure 2. Shares of indirect energy associated with manufacturing, service and scrapping of vehicles registered in Sweden.

3.3 Fuels

The primary fuels used for propulsion in road transport in Sweden are petrol and diesel. Fossil gas, biogas and other alternative fuels such as alcohols make up a minor share, denominated ‘other fuels’ below (average data for 1998-2002, Swedish Energy Agency 2003, it should however be mentioned that the share of alternative fuels has presumably increased in Sweden during the last couple of years, which is not included in the figures below):

- Petrol; 171,648 TJ/year
- Diesel; 97,728 TJ/year
- Other fuels; 840 TJ/year

The indirect energy related to these fuels, as shown on the calculation sheet, is calculated by additions (see section 2.8) to the total energy content accounted for propulsion. The addition for the alternative fuels is estimated to 15%.
The approach used in this paper is somewhat simplistic in the sense that no deduction has been made in the calculation considering fuel (mainly diesel) used in the construction and maintenance of infrastructure. It is not known how much of this energy is included in the figures above (which should concern road transport only) and how much is accounted for under other industrial activities in the energy statistics. It is possible that truck transport made in connection with for example road construction are counted as road transport, whereas the energy used by the diesel-driven working machines that are used for logging, excavation, earth-moving, overburden removal, blasting and rock drilling (which consumes the lion's share of the energy used in the pre-treatment of road construction) is not. This simplification may contribute to some double counting, but the effect on the results – which probably would entail that the share of indirect energy in reality should be larger – is assumed to be marginal. It is also reasonable to assume that there is an element of diesel used for road transport that actually is designated and taxed (and thus posted) as fuel for working machines. In a similar fashion, no deductions have been made for the fuel used in the transportation of fuels, but this is appraised by Cordi (1979) to be a marginal source of error.

3.4 Annual energy associated with Swedish road transport

Table 4 shows the calculation sheet summarising annual energy associated with Swedish road transport, based on section 3.1-3.3. The energy unit used in table 4 is TJ.

Table 4. Annual energy associated with Swedish road transport [TJ]

Indirect energy					**Total**	**(%)**	**(%)**
Infrastructure	**Motorways**	**Public roads**	**Streets**	**Private roads**			
Construction	10382	46682	17853	14828	89745	81.9	
Operation	253.5	3386	1073	670	5382.5	4.9	
Maintenance	1305	6966	4736	1480	14487	13.2	
Total	11940.5	57034	23662	16978	109614.5	100	
Share (%)	10.9	52.03	21.6	15.5		100	22.1
Vehicles	**cars**	**buses**	**trucks**	**Other**			
Manufacturing	34562	1256	8687	2750	47255	65.9	
Service	18456	2580	2642	3113	26791	37.3	
Scraping	-1530	-47.5	-712	-4.2	-2293.7	-3.2	
Total	51488	3788.5	10617	5858.8	71752.3	100	
Share (%)	71.8	5.3	14.8	8.2		100	14.5
Fuels	**Petrol**	**Diesel**	**Other**				
Production	30897	13030	126		44053		
Share (%)	70.1	29.6	0.29			100	8.9
Total					225420		45.5
Direct energy							
Fuels	**Petrol**	**Diesel**	**Other**				
Propulsion	171648	97728	840		270216		
Share (%)	63.5	36.2	0.31			100	54.5
Total					495636		100

Table 4 shows that the share of indirect energy taken together is calculated to 45.5% of total energy use. When it comes to infrastructural energy (22.1%), the construction phase dominates. The ordinary public roads can be accounted for more than half of the infrastructural energy, which of course is not surprising since that type of road is the most common in Sweden. When it comes to vehicles (14.5%), manufacturing in general, and manufacturing of cars in particular, dominates. It is also interesting to note that the indirect energy associated with fuels almost constitutes a tenth of total transport energy (8.9%).

4. The effects of some hypothetical strategies to reduce energy associated with road transport

One purpose of the comparison of quantities and shares in the previous sections was to identify the potential for improved efficiency and reduced energy use. A discussion on this topic, with the calculation sheet as a starting point, can lead to insights such as the following: The energy that is saved through the recycling of metals in the scrapping of a car in Sweden corresponds to roughly 0.05% of the lifetime fuel consumption of the same car. Or, that Swedish motorway construction, on an annual basis, roughly corresponds to a decade's consumption of alternative fuels such as biogas and alcohols.

By using the calculation sheet, the efficiency of hypothetical measures, whose aims are described below, can be examined in a more structured manner. The outlined scenarios should however not be considered a thoroughly substantiated chain of events that leads to predictable quantitative results, but rather qualitative descriptions of goals and related energy magnitudes. Only the road sector is addressed in this calculation exercise. This is a simplification, as possible changes in the distribution between various modes of transportation (e.g. railroad and air traffic) is not taken into account.

The hypothetical scenarios that are reviewed in the calculation model are the following:

1. New priorities in public funding – half as many new roads constructed.
2. More efficient use of vehicles – a fifty percent reduction of the Swedish car fleet.
3. More efficient vehicles – fuel consumption for cars cut in half.
4. Less transport work – all road transport reduced by half.

One purpose of the following calculation examples is to estimate the size of the effect of individual action strategies. Even though the scenarios are not very realistic as isolated events, there can be reasons to examine the measures individually in order to get an idea of their impact, and in a longer perspective possibly prioritise among designated measures. However, even though they primarily target one specific energy category, most measures will affect others as well. The various energy items depend on each other, as was discussed in section 2. The assumptions that are made in order to include changes that depend on the mutual connections among the energy items are specified for each scenario in question.

4.1 Scenario 1: New priorities in public funding – half as many new roads constructed

In the long run, less road construction can be assumed to lead to less energy being required for operation and maintenance as roads are closed down. On the other hand, it is reasonable to assume that there will be an increased need to extend the lifetimes of the existing roads (since transport volumes do not change in this scenario), which in that case would increase the energy quantity spent on maintenance. In this simplified calculation example, the energy

for operation and maintenance is assumed to remain at current levels. Another simplification that has been made is the disregard of any possible dynamic effects of reduced road construction. It has been shown that new roads often lead to increased transport volumes, i.e. infrastructure induced transport (e.g. SACTRA 1994; ECMT 1996). Such possible, yet opposite, effects have not been taken into account here.
Compared to the present situation, scenario 1 would entail a total energy reduction of approximately 9% (see table 5).

4.2 Scenario 2: More efficient use of vehicles – a fifty percent reduction of the Swedish car fleet

A fifty percent reduction of the Swedish car fleet (perhaps due to a massive support, and subsequent increase, of car-sharing) with everything else, including transport volumes, remaining the same, would of course entail a reduction in manufacturing energy. However, since the vehicles are assumed to be used with a double intensity, the need for service would increase; alternatively their lifetimes would be reduced. Vehicles fall into decay not only through use, but due to wind and weather as well. Therefore a twofold increase of service energy has not been assumed, but rather an increase of 75%, for half as many cars compared to the current situation. The energy that can be saved through recycling in connection with scrapping is reduced by half.
This example only refers to cars, which at present have a relatively low level of use. Trucks and buses are subject to a significantly higher intensity of use.
Compared to the present situation, scenario 2 would entail a total energy reduction of approximately 4% (see table 5).

4.3 Scenario 3: More efficient vehicles – fuel consumption for cars cut in half

More efficient vehicles – perhaps as a result of major breakthrough for environmental cars – would entail a reduction in the use of fuels, and also considering fuel production. However, the infrastructure, the quantity of vehicles and transport volumes will remain the same in this example. This scenario does not necessarily require any new technology. There are already cars available today that use conventional technology to minimise fuel consumption. In the case of automobiles it may rather be an issue of prioritizing between vehicle weight, energy-demanding extra gear, motor strength, and whether the car is optimized for high or low speed. It is much harder to reduce fuel use in buses and trucks, where commercial incentives already have spurred the demand for more efficient vehicles. In this example, the fuel consumption of trucks and buses is assumed to remain unchanged (the specific quantities of fuels for cars, buses, trucks, and other vehicles respectively, is based on processed data from Åkerman and Höjer, 2006).
Compared to the present situation, scenario 3 would entail a total energy reduction of approximately 25% (see table 5).

4.4 Scenario 4: Less transport work – all road transport reduced by half

The scenario involving a fifty percent reduction of all road transport, which corresponds to pre-1970s levels, would – everything else remaining the same – likely require the most radical changes in the people's everyday lives, but would also entail the largest impact on energy use. A halving of transport volumes would in reality entail a lesser need for new

roads, but this calculation example is based on current construction rates. Operation of infrastructure is not affected either in accordance with the earlier assumption that most functions are required regardless of intensity of use. Maintenance energy however is affected. There is less wear caused by use, but climate-related decay remains unaffected. A forty percent reduction is assumed. It could be argued that the vehicle population would shrink as a consequence of this scenario, at least as far as trucks are concerned, since it would be unprofitable to maintain the same number of vehicles when volumes decrease. However, for the sake of simplicity, the vehicle population is assumed to be intact, while the need for service is reduced due to less wear. As for energy related to service, a forty percent reduction has been assumed.
Compared to the present situation, scenario 4 would entail a total energy reduction of approximately 35% (see table 5).

Table 5. Present situation and scenario 1-4 of annual energy associated with Swedish road transport

	At present (table 4)		**-50 % new roads**		**-50% cars**		**-50% fuel consumption**		**-50% transport work**	
	[TJ]	**[%]**	**[TJ]**	**[%]**	**[TJ]**	**[%]**	**[TJ]**	**[%]**	**[TJ]**	**[%]**
Infrastructure	109,615	22	64,742	14	109,615	23	109,615	30	103,820	32
Vehicles	71,752	15	71,752	16	52,929	11	71,752	19	61,036	19
Fuel prod.	44,053	9	44,053	10	44,053	9	26,432	7	22,027	7
Indirect, total	225,420	46	180,547	40	206,597	43	207,799	56	186,883	58
Direct, total	270,216	54	270,216	60	270,216	57	161,216	44	135,108	42
Total	495,636	100	450,763	100	476,813	100	369,015	100	321,991	100
Reduction	-	-	44,873	9	18,823	4	126,621	25	173,645	35

5. Discussion

The calculations presented in this paper show that indirect energy can definitely not be neglected, but rather constitutes a considerable share of the total energy use in the Swedish road transport sector – approximately 45%. But even though the indirect energy as a whole may appear surprisingly large, the energy use is still dominated by the consumption of petrol and diesel for propulsion. The comparison between the four hypothetical energy reduction scenarios leads to ambiguous conclusions. On the one hand, indirect energy constitutes a considerable share. On the one hand, the most effective reductions address direct energy use. Although indirect energy is substantial, it is less impressionable – being embodied in infrastructure and vehicles – than the direct energy use. Due to the influence of indirect energy however, a 50% reduction of fuel consumption for cars – which by all means must be seen as a major change – only leads to a 25% reduction in total. This illustrates the magnitude of the challenge involved in radically reducing transport energy use. The main pedagogical contribution of the calculation exercise with the hypothetical scenarios is that isolated measures, although rather drastic, do not exert full effect on the transport sector in its entirety – halving the consumption of petrol and diesel does not automatically entail a halving of total transport energy, and neither for that matter a halving of the related environmental effects.
The insight into the significance of indirect transport energy should have implications on policy-making processes, e.g. the design of means of control that affect the energy use and

environmental impact of the transport sector. For example, in order to forcefully reduce road sector CO_2-emissions, decision-makers should not focus exclusively on the use of petrol and diesel for propulsion. Even though direct energy use remains the individually largest energy item, energy use associated with infrastructure and vehicles cannot be disregarded. The impact of energy and environmental policy probably depends on the combinations of measures that on the one hand act as incentive to improve efficiency, and on the other hand focus both on fixed and variable items. In other words, the central issue is not only the actual travel and transport of goods, but also the conditions that make transport possible, i.e. vehicles, infrastructure and fuel production.

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