Vägverket

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On the Road to Climate Neutral Freight Transportation

– a scientific feasibility study

Preface

An efficient freight transportation sector is a necessary component of a modern growth-oriented society. But today's freight transportation accounts for significant emissions of carbon dioxide, the major greenhouse gas. Mitigating climate impact from the transportation sector is a serious challenge, not least because this sector is so highly dependent on fossil fuels. Since the beginning of the 1990's, a number of measures have been implemented: vehicles and engines have become much more fuel efficient, shipments have been made more efficient, and renewable fuels have been introduced. But in order to make possible a transition to carbon neutral transportation, additional major initiatives are required. Collaboration between various stakeholders in the transportation sector, other business and industry agents, society as a whole, and the research community needs to expand, to accelerate this development.

For this reason, the Centre for Environment and Sustainability at Göteborg University and Chalmers Institute of Technology, Preem, Schenker, Volvo Trucks, and the Swedish Road Administration are partnering On the Road to Climate Neutral Freight Transportation. The objective is to show how to reduce emissions associated with freight transportation by road in Sweden and how the various stakeholders can contribute. The collaboration focuses on improving shipping efficiency, fuel production efficiency, vehicle efficiency, as well as expanding the use of renewable fuels.

In order to provide a scientific basis for this collaboration, a feasibility study has been performed by Fredrik Hedenus, Department of Physical Resource Theory, Chalmers Institute of Technology.

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1. Introduction

The most recent Assessment Report by the UN panel on climate change (Intergovernmental Panel on Climate Change, IPCC) has determined that it is very likely that human emissions of greenhouse gases have impacted global climate already. The global average temperature has increased by 0.6°C since the pre-industrial era (IPCC, 2007). If emissions continue to increase, the global average temperature will increase between 2 to 6°C over the next century (IPCC, 2007). However, the uncertainty associated with the climate impact of a given amount of greenhouse gas emissions is still large. Currently, the average Swede is responsible for roughly 7.5 tons CO_2-eq per year (EPA, 2006). World-wide, annual average emissions must be below 2 tons CO_2-eq per person by 2050 in order to make likely that the increase in global average temperature stays below 2°C. This presents a major challenge for Sweden although the challenge is all the more formidable for others. In the US, for instance, current annual emissions amount to roughly 25 tons CO_2-eq per capita.

Carbon dioxide is the most important greenhouse gas resulting from human activity. Currently, it accounts for 79% of climate pollution in Sweden (EPA, 2006). Methane, mainly from ruminants and landfills, and nitrous oxide, mainly from nitrogen fertilizer spread on agricultural land, are next in importance. With respect to transportation, current greenhouse gas emissions mainly consist of carbon dioxide, but if the share of biofuels increases, nitrous oxide emissions will also increase.

Carbon dioxide emissions from the transportation sector have been under scrutiny in Sweden during the past few years. This scrutiny has focused on passenger travel, rather than freight transportation, despite the fact that freight transportation by road is growing faster than passenger travel by road. Today, the transportation sector accounts for 30% of Swedish greenhouse gas emissions, and freight transportation accounts for 6%. However, emissions from passenger travel have stabilized the past few years, while emissions from freight transportation by road have increased by 8% in the past 15 years (SRA, 2006).

The climate change problem necessitates a large transition which entails that each sector must determine, and plan for, possible ways to reduce emissions. This report considers freight transportation by road. Our purpose is mainly to consider measures the partners commissioning the report, Preem Petroleum, Schenker, Volvo Trucks, and the Swedish Road Administration, can work on together. For this purpose, we mainly consider logistics, engines, and fuel. Questions pertaining to transitioning from road to rail or relocating industries are outside the scope of this study and will only be considered tangentially.

This report is structured as follows: in Chapter 2, we characterize freight transportation in Sweden in its entirety as well as provide a more detailed description of freight transportation by road and its development over the past 20-30 years. In Chapter 3, we discuss long-term options for reducing greenhouse gas emissions by almost 100%. In Chapter 4, we describe the potential for emissions reductions by 2015 and give rough estimates for the period 2025-2030. We also discuss policy instruments and strategic measures for the future.

2. The current situation

2.1 FREIGHT TRANSPORTATION IN SWEDEN

Freight transportation is an important factor in industrialized societies. Raw materials are transported for processing, products are transported to suppliers who ship components to manufacturing, and end products are delivered to consumers. Waste materials are brought back for materials- or energy recycling or for deposit at landfills. Historically, freight transportation has increased in parallel with economic growth. Since 1980, GDP has grown by 68%, and transportation work (measured in ton-km) has grown by 43%, see figure 1.

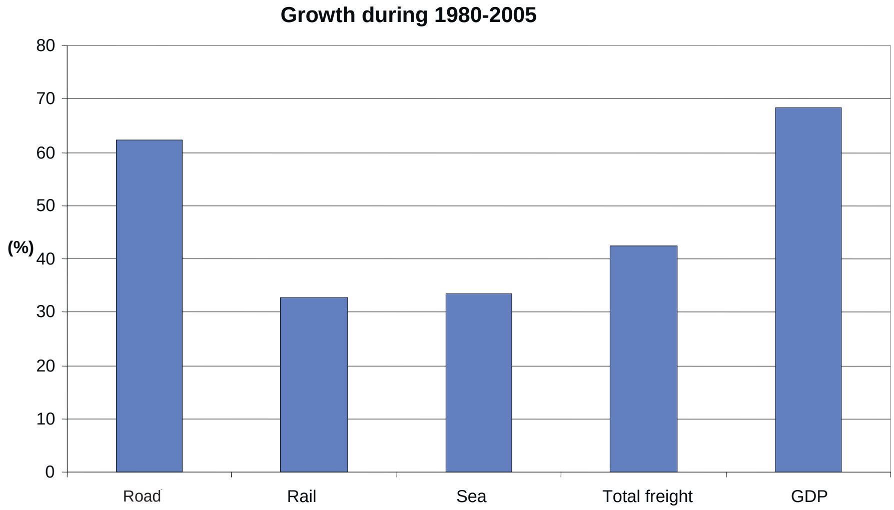

Figure 1. GDP growth and growth of transportation work for different transportation modes during the period 1980-2005 (SCB, 2006; SIKA, 2005c).

There are three main modes of freight transportation: road, rail, and sea. Air freight is also used for domestic transportation, but due to the high cost, only 0.4% (by weight) of freight is carried by air (SCB, 2001). Road transportation grew almost as fast as GDP during this period, see figure 1, i.e., faster than transportation as a whole. This has entailed an increase in the portion of transportation work by road, from 32% in 1980, to 37% in 2005 (SCB, 2005). However, compared to the rest of Europe, a relatively large portion of Swedish transportation is by rail. Only the former Eastern Bloc nations have a higher rate of transportation by rail (EEA, 2006).

On average, transportation by road requires 10 times the energy per ton-km compared to rail and sea, see figure 2. The shift toward more transportation by road has therefore increased the total transportation energy demand. From a climate perspective, a shift toward rail and sea would be advantageous. However, shifting large amounts of cargo to rail has proved difficult. Transportation by road is much more flexible, and rail availability is frequently under-dimensioned, resulting in slower transportation by rail.

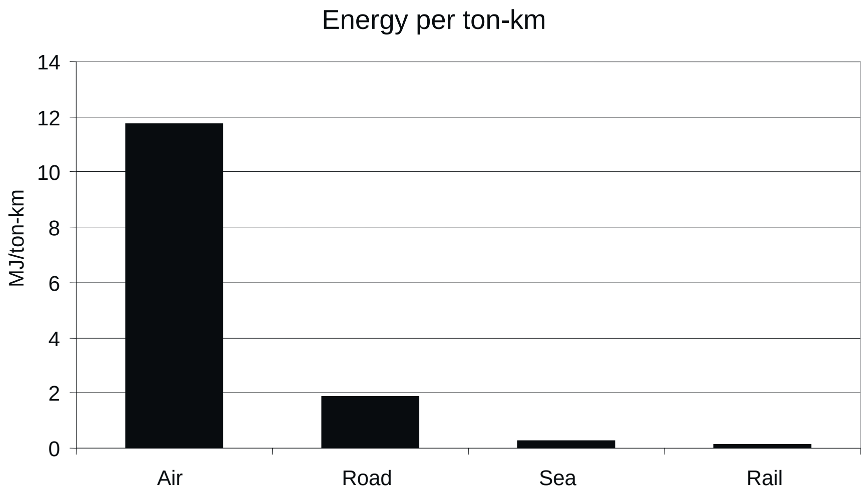

Figure 2. Average energy use per transportation utility for various transportation modes (IVA, 2002).

2.2 TRANSPORTATION DEMAND

The most climate-friendly shipment is of course the one that never takes place at all. But while the perpetual discussion regarding unnecessary transportation continues, transportation continues to grow. So, what are the opportunities for establishing a society with less transportation, or one in which transportation is at least stabilized?

Systems that involve large centralized warehousing instead of more decentralized storage require more transportation. Current transportation costs make central storage economically advantageous. In order to make a more decentralized structure cost-efficient, transportation costs must double, at least, according to estimates (McKinnon, 1999).

The distances between production, raw materials extraction, and consumption also affect transportation demand. Factors other than transportation costs, such as salaries, know-how, and supply of raw materials in different regions and nations largely determine location. Estimates show that in order to establish largely regional markets and thereby reduce shipments, transportation costs would need to increase five-fold (McKinnon 1999). Because fuel costs account for only 20-30 % of transportation costs, fuel costs would need to rise 20-fold. At that price, fuels with very low greenhouse gas emissions would long since be competitive. From a purely economic perspective, changing technology rather than the structure of transportation seems closer at hand. We will probably have to live with global freight transportation. However, there is a small opportunity, even at current energy prices, to reduce demand for freight transportation through physical planning.

The fact that we are moving toward a service society is sometimes used to suggest that transportation of goods therefore will decrease. True, we are spending more of our income on services. However, it is easier to increase the efficiency of producing goods than of producing services. This means that the price of goods falls more rapidly than the price of services. Thus, while we increase the portion of income spent on services, we are still consuming an increasing amount of goods—and these need to be transported (Kander, 2005). A transition to a more service-based economy is therefore not in and of itself a transition to a society with a reduced increase in freight transportation. In the EU, transportation per GDP has increased between 1992 and 2003 (EEA, 2006), despite all the talk about the new service economy.

2.3 FREIGHT TRANSPORTATION BY ROAD

The benefit of freight transportation by road is its flexibility, but the relatively high emissions of greenhouse gases per ton freight shipped, compared to rail or sea, constitute a drawback. The total weight of freight by road has decreased in Sweden in the past 20 years from 447 million tons in 1970, to 349 million tons in 2005 (SCB, 2007). But the freight is transported a longer distance, which means that ton-km have increased steadily. In Sweden, but also in the EU as a whole, there is a strong correlation between transportation work by road and economic growth (Åhman, 2004; Tapio et al, 2007). For this reason, we can expect transportation work to increase if we see continued economic growth. However, there are differences in growth for the different types of freight. Partial load packaged freight has increased the most and constitutes half the freight in Sweden (see figure 3).

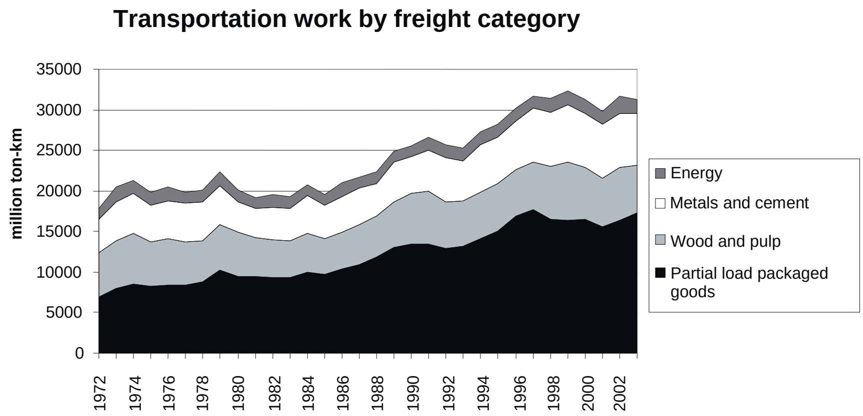

Figure 3. Transportation work by road has nearly doubled in the past 30 years; partial load packaged goods have increased the most (SIKA, 2007).

More than 90% of all transportation work in Sweden today is done with heavy trucks, mainly on long-distance hauls, as can be seen in figure 4. Medium trucks, 12-32 tons, account for 8% of transportation work but for 17% of carbon dioxide emissions. These trucks take smaller loads but are also used more in city traffic where fuel economy is roughly 20% lower than on the highway (Hammarström and Yahya, 2001). Although light and medium trucks emit more carbon dioxide per ton-km, the great potential for reducing emissions resides with heavy trucks.

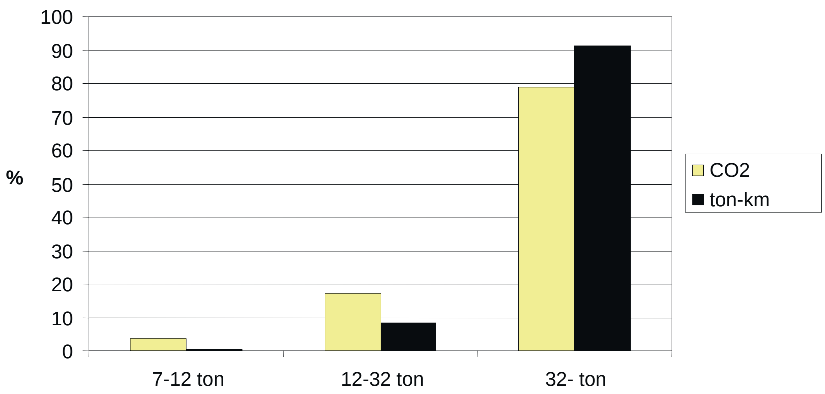

Figure 4. Share of transportation work and carbon dioxide emissions by truck weight (SIKA 2006b and SRA 2006).

Generally speaking, the share of long-distance shipments is growing. Gravel and unprocessed minerals are still being transported short distances by road. The percentage of partial load goods has mainly increased on 100-300 km hauls, while their share of short distance runs has decreased, see figure 5.

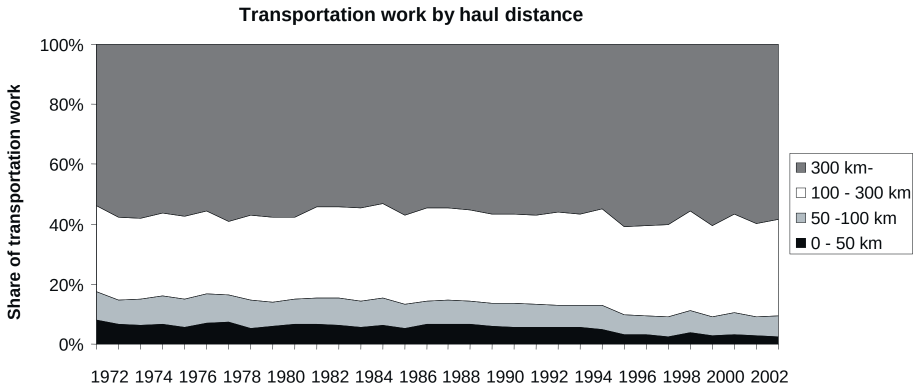

Figure 5. Share of total transportation work for partial loads goods by distance shipped (SIKA, 2007).

The average carbon dioxide emissions per ton-km are an important aspect of freight transportation development. For any given shipment, both emissions and the specific conditions can vary significantly from one ton-km to another. But in order to study changes in the transportation system as a whole, the ton-km unit is most appropriate.

Historically speaking, average carbon dioxide emissions per ton-km fell almost 25% from 1990 to 1997. However, thereafter, the trend appears to have turned around, and emissions have held steady during the past decade, see figure 6. Short-term fluctuations are not very significant and may simply reflect data errors. However, we can see that the declining trend during the nineties has stopped.

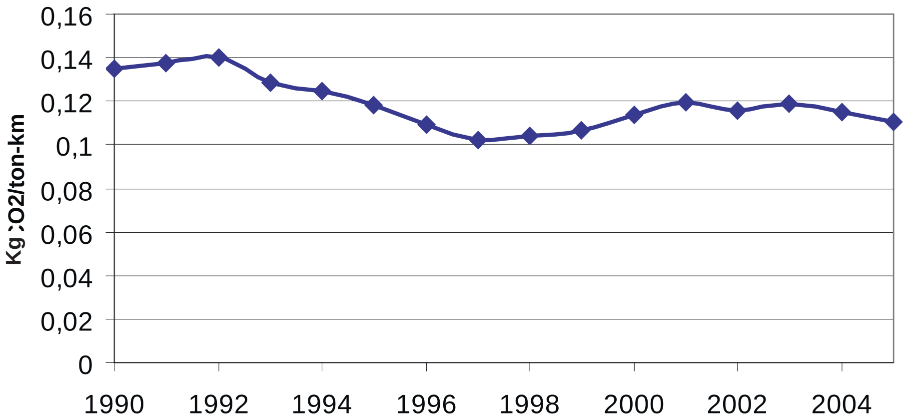

Figure 6. Average carbon dioxide emissions per ton-km in Sweden (SRA, 2006; SIKA, 2007).

According to Volvo, truck fuel economy has improved by 23% since 1990 (Mårtensson, 2006), and data from SRA indicate that the effective fuel economy has improved 22-23% from 1990 to 2006 (SRA, 2006). However, the figures are not directly comparable. The Volvo figure compares a 1990 truck to a 2006 truck. The SRA figure represents not only fleet improvements but also any changes in driver behavior. But no major changes appear to have taken place; for example, truck highway speed has not increased (SRACS, 2005). Therefore, the Volvo data match actual history quite well. This suggests that Scania, the other large truck manufacturer in Sweden, has seen similar progress in efficiency. The improvements in fuel economy are due to vehicle improvements, but better fuels with lower levels of sulfur have also contributed.

Most of the efficiency gains were had between 1990 and 2000. Since then, the increase in efficiency has only been 5%, which also matches the Volvo data and the trend in emissions per ton-km shown in figure 6.

During this period, heavier trucks have consumed a growing share of diesel (SRA, 2006), while the freight is being transported longer and longer distances. This means a smaller amount, relatively speaking, is shipped in smaller trucks in cities, while more and more is shipped in heavier trucks on the highway. This has contributed to a reduction of the average emissions per transportation work.

The share of partial load goods has grown, and this kind of freight typically results in higher emissions per ton-km since it is constrained by volume rather than weight. This means more trucks for any given weight than for less voluminous freight. The increase in this kind of freight has therefore contributed to an increase in emissions per ton-km.

In order to reduce carbon dioxide emissions, low blend diesel with biodiesel was introduced in the early 1990's. However, the share is so miniscule, less than 0.5% of the total diesel use in 2005 (STEM, 2006), that this has not had any significant impact on transportation climate efficiency.

The share of no-load runs, runs with no shipments, shrank from 28% in 1993 to 25% in 1995 but has remained fairly constant since (SIKA, 2005, pp 75). Apart from no-load runs, the most important logistics data is the load to load capacity ratio. The average ratio can be estimated by dividing the ton-km by total distance for each truck class. Including no-loads and weighting by the amount of freight transported in each vehicle class yields an average load to load capacity ratio of 34%. This figure has been constant from 2000 to 2006. (SIKA, 2001; SIKA, 2002; SIKA, 2003; SIKA, 2004; SIKA, 2005b; SIKA, 2006b). From 1985 to 1995, the ratio is estimated to have decreased by 4% (REDEFINE, 1999).

Historically speaking, there has been a trend toward more climate efficient transportation. The most important factor is improved truck fuel efficiency. Another factor is the shift toward heavier trucks and more long-distance hauls. Rate of improvement overall has decreased the past five years.

3. The future

To allow for climate neutral freight transportation in the future, we need large changes in drive trains, fuel, and transportation efficiency. In this chapter, we will look at hydrogen, fuel cells, and biofuels. To what extent can these technologies replace today's diesel-dominated system? How can these new technologies be made as climate neutral as possible? We will also consider future improvements in shipping efficiency. Presumably, efficiency will grow even more important, as the cost of climate neutral fuel is expected to be higher.

3.1 HYDROGEN AND FUEL CELLS

Hydrogen is not an energy source but an energy carrier. Hydrogen has to be produced using an energy source. When hydrogen is used in a fuel cell, the exhaust is just water vapor. In order for hydrogen to be considered climate neutral, its energy source has to be climate neutral. There are three main climate neutral energy sources for hydrogen production: renewable energy, fossil fuels with carbon capture and sequestration (CCS), and nuclear power.

The top candidate for large-scale renewable electricity generation in the short and midterm is wind power. However, wind turbines will need to be complemented by power storage technology, for large scale applications, in order for wind power to provide electricity when there is little or no wind.

Excess power can be used to split water to make oxygen and hydrogen; this hydrogen can be stored to generate power as needed. The potential for wind power in Sweden is roughly 29 TWh electricity (STEM, 2003); freight transportation by road uses ca 16 TWh diesel. When losses from various energy transformation steps as well as the higher efficacy of fuels cells have been considered, these 29 TWh wind power converted to hydrogen could fuel almost twice the current transportation work.

Fossil fuels with CCS would allow us to continue to use fossil fuels without emitting carbon dioxide into the atmosphere. Instead of the gas being emitted, it is captured and sequestered in aquifers and empty oil or natural gas fields. Making this work requires large facilities; we cannot capture the emissions from an individual car. CCS is still under development, but several pilot projects are underway in Europe. Through biomass gasification, hydrogen can be generated from biomass, too. However, it is clear that from an economic perspective, it should be more cost-efficient to use biomass to produce liquid fuels than to generate hydrogen.

Hydrogen can also be generated using nuclear power. The potential is large, and the cost is relatively low. The future of nuclear power is a political question. Solutions need to be found to the waste storage problem, the safety risks, and the increased risk of nuclear proliferation associated with global use of nuclear power.

3.1.1 FUEL CELLS AND HYDROGEN STORAGE

A fuel cell does not burn hydrogen gas. Rather, a chemical reaction generates electricity. The top hydrogen fuel cell efficiency is 60% (Jeong and Oh, 2002). The top diesel engine efficiency is just above 50%. Fuel cells are highly efficient for a wider range of loads, while a diesel engine quickly loses efficiency at low loads. This means that the efficiency gains for fuel cells are greater for deliveries than for long-distance hauls.

One considerable problem associated with hydrogen gas is its low energy density. For this reason, hydrogen has to be stored at high pressure or at -253°C to yield liquid hydrogen—or else one tank's worth of hydrogen would not yield an acceptable range. Pressurized containers or tanks for maintaining this low temperature are voluminous and heavy. A long-distance truck would need a tank size of roughly 7.5 m^3 for pressurized hydrogen in order to offer the current range. For liquid hydrogen, the tank would need to be 1.7 m^3 (based on Burke and Gardiner, 2005 and IEA, 2005).

However, almost 30% of the energy content is used just to keep the hydrogen in liquid form; for pressurized hydrogen gas at 700 bar, the corresponding figure is 10% (Bossel and Eliasson, 2003). Research is underway regarding binding hydrogen to metal hybrids, but this does not appear promising, currently. Distribution of pressurized or liquid hydrogen also places severe demands on tank trucks and pipelines. For this reason, some energy losses and fairly high distribution costs should be expected (Bossel and Eliasson, 2003).

In addition to the storage question, there are several barriers to large-scale implementation of fuel cells. The average life of a vehicle fuel cell is 100,000 km, too short for commercial transportation (IEA, 2005). The cost is also a barrier. Today, fuel cells cost 40 times more than a passenger vehicle engine. According to the IEA, this figure could go down from 40 to 3 in the coming 30 years. The most optimistic estimates project fuel cells on a par with combustion engines (IEA, 2005). But it is abundantly clear that this will take significant research and development.

3.1.2 FUEL CELLS IN TRUCKS

There are important barriers to the use of fuel cells for freight transportation. If the cost barriers are surmountable, fuel cells may be an interesting solution for deliveries. The range requirements are not as demanding which means that 700 bar tanks may be a reasonable solution. Additionally, the efficiency gains are greater than for long distance transportation. Long distance traffic will most likely require liquid hydrogen storage. That would entail large energy losses at the distribution level which would increase the cost. Further, the efficiency gains over the diesel engine are smaller. Therefore, the use of fuel cells in long-distance transportation appears difficult.

3.2 BIOFUELS

3.2.1 CLIMATE NEUTRAL BIOFUELS

Several different kinds of biofuels can be used for freight transportation. Liquid biofuels have two serious competitive advantages relative to hydrogen and fuel cells: biofuels are energy-dense and existing engine technology can be leveraged. However, ensuring the climate neutrality of biofuels is harder, as is ensuring sufficient future supply.

Four conditions must be met in order for a particular biofuel to be considered climate neutral. First, the full amount of harvested biomass must be replaced by new growth; the carbon dioxide has to be accounted for in the carbon cycle associated with feedstock cultivation. Second, the agricultural practices must not reduce the amount of carbon in the soil. Third, energy used to produce the fuel must be climate neutral. This includes fuels for equipment and transportation, energy for fertilizer, as well as the energy used in the processing plants. Fourth, greenhouse gas emissions other than carbon dioxide must be low or compensated for in some manner.

However, the suitable future fuel must not only be climate neutral. Land efficiency is another important criterion. If the global aim is toward low emissions, the demand for biofuels will grow. This in turn will increase the demand for land. A higher demand for land will result in higher food prices as well as more interest in clearing natural forests for agricultural land.

Connected to the issue of land efficiency, a biofuel must be able to offer a solution for a large part of the global market. Sweden cannot have a unique solution for freight transportation. That would be too expensive. However, the prospects are good for local use of resources such as biogas, but these alternatives will not be able to cover the lion's share of future freight transportation in Sweden.

3.2.2 ANALYSIS OF BIOFUELS

The biofuels of relevance for diesel engines are biodiesel, i.e., FAME, fatty acid methyl ester, which is made from various kinds of oil crops, currently mainly from rapeseed oil. When made from rapeseed oil, the fuel is called RME, rapeseed methyl ester. Vegetable and animal oils can also be hydrogenated to form a fuel very similar to diesel. Very little has been published about these oils, but indications are that their life cycle emissions are somewhat lower than those of FAME (UOP, 2005). Because of the paucity of information, hydrogenated oils will not be considered here. Two other fuels made by process of gasification of woody biomass, namely Fischer-Tropsch-diesel (FTD) and dimethyl ether (DME), are at the development stage.

FAME and FTD can be blended in regular diesel and used in regular diesel engines, possibly requiring minor modifications. DME is a gas fuel which turns liquid already at 3-5 bar pressure. For this reason, it is relatively easy to transport and store, but it cannot be blended in conventional diesel. DME requires a somewhat modified engine as well as a special kind of fuel tank.

Figure 7 shows energy extracted per land unit, as well as greenhouse gases, by fuel type, in a system where all liquid fuels required for production are biofuels, and all power and heat is from biomass. Additionally, all waste products from production are used for heat or power. This is a reasonable assumption when considering long-term feasibility. In the short run, and in smaller amounts, FAME may have better environmental performance because animal feed is produced as a byproduct which could mean reducing soy imports. However, should all European freight transportation run on FAME, there would not be a market for all the feed. A similar phenomenon arises for DME and FTD which can be produced by gasification of black liquor, a byproduct from chemical paper pulp, at a lower cost and with better environmental performance than if a woody biomass feedstock is used. But the supply of black liquor is too small to fuel a greater part of freight transport-ation in the EU.

The estimates in figure 7 are intended to indicate relative values, not the exact absolute values. DME has the lowest emissions and land requirements. Emissions from FAME are half those of conventional diesel, despite all inputs being from biomass. The main reason behind this is the relatively large N_2O emissions associated with rapeseed cultivation. A certain amount of methane emissions also contribute (Concawe, 2006).

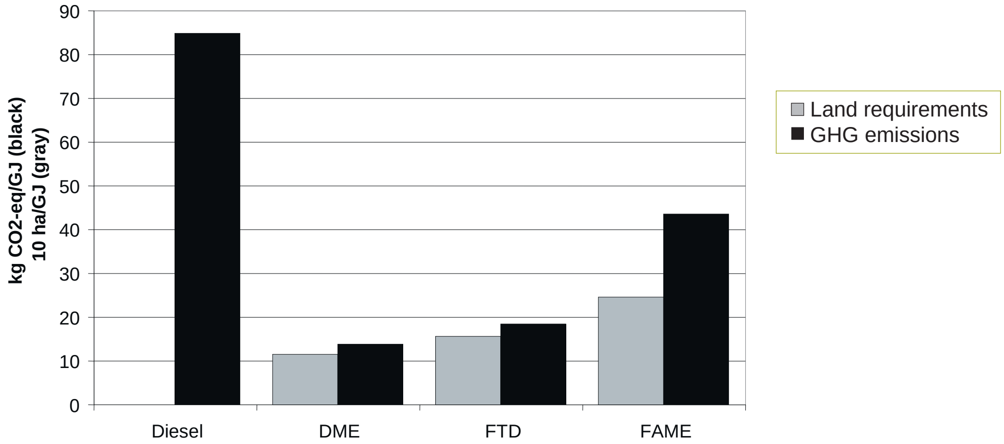

Figure 7. Greenhouse gas emissions and land requirements per GJ fuel by fuel type. Transportation fuel input for a given type is assumed to be that type, and all waste products are assumed used for energy. Based on Jonasson and Sanden (2004) and SRA (2001).

3.2.3 POTENTIAL SUPPLY OF AND COMPETITION FOR BIOMASS

Bioenergy is a renewable resource, but it is not without limit. What is the future potential for biofuels? Productive land is a finite resource, and in a bioenergy future this land must produce not only food for the world, but also energy. Therefore, any estimates of potential supply face difficulties. There are significant unknown parameters, such as the future relative ability and willingness to pay for food and bioenergy, the extent to which environmental priorities will be respected, and to what extent agriculture and forestry will be intensified through for example fertilization. Nevertheless, we will provide a rough estimate.

Today, transportation by road in Sweden uses 86 TWh of which freight accounts for 16 TWh. The potential for RME from rapeseed oil in Sweden is estimated at 1 TWh in 2020 (STEM, 2007b). At the EU level, rapeseed potential is also very limited (Concawe, 2006). Vegetable-based oils can be imported from other parts of the world. However, there is a risk that this import will be palm oil from Southeast Asia. It is well-known that the spread of palm oil plantations is contributing to the destruction of rainforest, which entails large emissions of carbon dioxide (Hooijer et al, 2006). Increasing the amount of biofuels blended in through imported palm oil can therefore at least in the short run increase emissions rather than decrease them.

When it comes to DME and FTD, these can be produced from woody biomass and black liquor, which have significantly greater potential than rapeseed from farmland. By 2020, black liquor is estimated at 45 TWh in Sweden (STEM, 2007b). This could provide 20-30 TWh transportation fuel. Currently, black liquor is used for power and heat. Thus, this energy needs to be replaced if the black liquor is instead used to make transportation fuel.

The Commission on Oil Independence (2006) estimates that in 2050, the supply of domestic bioenergy could be 110 TWh greater than today. If all this biomass were to be converted to transportation fuel, it would yield ca 55 TWh biofuels. This could provide for future freight transportation, but could not meet the demand from the road transportation sector as a whole.

However, bioenergy is traded on the global market; therefore it can be imported from other areas. But other areas will also make demands on that supply, especially once more nations implement serious climate policy. Further, not only freight transportation will demand bioenergy. Bioenergy can be used to generate power and heat as well as fuel for passenger travel and air transportation. Global cost-efficiency studies assuming ambitious climate targets have shown that bioenergy is more cost-efficiently used for heat and process heat than for biofuels (Azar et al, 2003). The study shows that gas and diesel are cost-efficient in the transportation sector until 2050, after which they are replaced by hydrogen. However, as we have seen, hydrogen is not an attractive option for long-distance shipping, which means that even if there is significant competition for bioenergy, biofuels for long-distance shipping may be relevant.

3.3 HYBRIDS AND PLUG-IN HYBRIDS

Hybrid technology is a means of increasing engine efficiency and thereby improving fuel economy. The most important difference between hybrid and conventional trucks is that hybrids have larger batteries and larger generators. Hybrid technology cuts fuel use in three ways: a combustion engine has low efficacy at low loads by running at high load even though the vehicle doesn't need this in order to run—the battery stores this excess energy thereby improving the engine's average efficiency. The stored energy can be used during stop-and-go driving, or when the engine needs extra power, for instance during acceleration. Finally, energy lost during braking is recaptured and stored in the battery. Simulations of hybrid vehicles point to savings of roughly 25% in city traffic for medium heavy trucks (An et al, 2000). Estimates for heavy trucks suggest savings of 34% in the city and 7% on the highway compared to current technology (Muster, 2000).

Hybrid technology can also be combined with fuel cell engines. The main gain in that case is that the fuel cell can be smaller since extra power during acceleration is provided by the battery. The gain in increased efficiency mainly stems from recapturing energy when braking, which can improve efficiency by 12% (IEA, 2005). The smaller gain compared to combustion engines is due to the fact that fuel cells have a high efficiency over a wider range of loads, compared to combustion engines.

Hybrid technology can be taken one step further by including a larger battery that can be charged from the grid. This is the so-called plug-in hybrid. This technology makes it possible to run on battery-only in city traffic while using the combustion engine for longer distances. 50 km of electric-only driving requires a 2,500 kg battery in a medium heavy truck (An et al 2000). Thus the range required for long-distance runs, 1,000 km, is beyond what current—and probably future—battery technology can provide.

If the electricity is climate neutral—i.e., from renewable energy, fossil fuels with CCS, or nuclear power—the electric powering of the vehicle will be climate neutral. In addition, local air quality would benefit.

Plug-in hybrids running in part on biofuels and in part on power from the grid may provide an appealing solution for urban deliveries.

3.4 MORE EFFICIENT SHIPMENTS

Improved efficiency will be of paramount importance for the freight transportation system whether we envision a fuel cell or a biofuel future. High vehicle efficiency will be particularly important for fuel cell vehicles, since this will relax hydrogen storage requirements. Measures to promote eco-driving, reduce air and rolling resistance, and improve engine efficiency are therefore all quite central.

Beyond actual engine improvements, estimates point to a potential to reduce fuel consumption by 30% by reducing weight and air resistance. Spoilers can result in efficiency gains of 4-8% and tire development may lead to fuel savings of 5-15%, albeit in some cases this would involve reduced traffic road safety (Nylund, 2006).

Both hydrogen and biofuels will also be more expensive than today's fuels; this will make efficient logistics even more important. There is a great potential for significant logistics improvements even if there are also large barriers. In Stockholm, modeling studies of produce distribution indicate that vehicle-km could be cut in half with optimized logistics. However, smaller distribution companies do not automatically collaborate in the ways required to make this system work. Co-distribution pilot projects in Europe and Sweden have been discontinued rather than extended, demonstrating this point (Blinge and Svensson, 2006). However, increasing transportation costs may change this situation in the future.

E-commerce also holds great potential for reducing transportation associated with everyday products and occasional items. But e-commerce does not automatically mean more efficient shipments. This requires either a large enough number of e-customers so that load to load capacity ratio is high or that different kinds of businesses co-ship. Further, practical systems for home deliveries need to be in place so that customers do not have to be present at delivery (Browne, 2001). A well-designed and optimized e-commerce system has the potential to significantly reduce transportation to the end customer.

Lumber shipments, which may seem simple compared to city delivery, have been shown to be able to be 15% more efficient through advanced optimization (FoF, 2006; Palmgren, 2005). This kind of potential probably exists for all freight traffic. However, advanced optimization algorithms will be required in order to leverage this full potential. But if such algorithms catch on among transportation companies in the future, this is likely to entail significant savings.

However, the really large promise for more energy efficient shipments is beyond the scope of this study: urban and regional planning and transportation mode transitioning. If society could plan to have as much transported into an area as is transported out, no-load "shipments" could be avoided entirely, theoretically speaking. If additionally these areas were connected by rail or sea, the energy required would also be reduced significantly. But such well-designed planning is hard if not impossible to achieve.

4. From here to the future

4.1 STRATEGY FOR CLIMATE NEUTRAL FREIGHT TRANSPORTATION

In order to achieve climate neutral freight transportation we need to take measures today. The strategy for reaching the goal can be seen as three-fold:

1. More efficient shipments: develop more efficient logistics systems which reduce the total transportation work, and adopt more efficient driving habits which improve fuel economy.
2. More efficient vehicles: better engines, combined with hybrid technology, especially for deliveries, reduced air and rolling resistance, and fuel cell technology development.
3. New fuels: blending of FAME, develop and demonstrate biomass gasification technology for DME and Fischer-Tropsch-diesel, fuel cell and hydrogen storage research to reduce costs and energy losses.

In this section, we will consider a number of measures within these three areas. We will discuss measures within each area and present estimates for the emissions reduction potential by 2015. We will also offer rough estimates for 2025-2030. Further, we will consider how these measures can put us on the road to climate neutral freight transportation and what policy instruments will make these measures possible.

4.1.1 METHOD

There are methodological problems associated with determining the potential for reductions. What we are trying to do here is to determine reasonable expectations on emissions reductions given the inertia in new investments, economic conditions, and technological development. Theoretically speaking, the potential is naturally much greater. If all trucks were replaced overnight, we could improve fuel economy much faster. Or if one logistics company were in charge of all transportation and optimized the entire system, this would allow for a substantial cut in shipments. But such theoretical estimates have little to do with what is achievable in the short run.

In order to estimate the potential for emissions reductions by 2015 we need to make a number of assumptions. These calculations pertain to improving the efficiency per ton-km of freight transported. The transportation system structure is assumed to be the same as today, that is, to have the same distribution of vehicle and product type. In the base case, we assume that emissions per ton-km are unchanged. During the 1990's the trend pointed down, but this does not seem to be the case any longer.

Different measures target different parts of the transportation system. For this reason, it is important to consider carbon dioxide intensity, i.e., the carbon dioxide emissions per ton-km, by sector of the transportation system. The calculations are corrected for difference in carbon dioxide intensity between distribution traffic (deliveries) and long-distance shipments, as well as for the fact that partial load goods are more voluminous, which means that the intensity is higher for this type of freight than for more compact freight. Partial load goods are weighted by a factor 1.4 based on data from Schenker (Ljungren, 2007).

Based on these assumptions, we estimate by how much emissions can be reduced by 2015 by the implementation of each measure. Because we assume that the transportation structure is the same as today, the actual emissions reductions in ton CO_2 only depend on the increase in freight transportation demand, by 2015.

We do not take into account one important aspect, the so-called rebound effect. According to the rebound effect efficiency gains result in lowered prices. This in turn results in higher demand, if other price-increasing measures such as taxes are not implemented. Therefore, some of the savings resulting from efficiency gains are canceled by the increase in demand. The rebound effect may apply to some of the measures we consider. This means that we will tend to over-estimate the actual effect the measures may have.

4.1.2 EFFICIENT SHIPMENTS

Coordinating road shipments

Collective freight transportation promises to improve some of Sweden's freight transportation. In 2005, 41% of transportation work was performed by company trucks and individually organized shipments (SIKA, 2006b); very little inter-company coordination takes place with these shipments. If some of this freight instead were handled by transportation logistics firms, the load to load capacity ratio could be improved and thereby emissions reduced. Mainly partial load goods shipped distances shorter than 100 km could be shifted to mass freight transportation. This kind of partial load goods accounts for 4.2% of total transportation work; we assume that this share holds for company trucks and individually organized shipments, too. These are mainly urban shipments with voluminous freight which means they need to be weighted higher than the average shipment. 25% of this freight could be shifted to mass freight transportation where we estimate efficiency is 20% higher (Schenker Consulting, 2003). To make this happen, shipment costs have to go up or else mass freight transportation has to receive incentives, for instance preferred treatment in city traffic. Should policy measures target mass freight transportation and the potential estimated above be realized, carbon dioxide emissions from freight transportation by road could reduce by 0.3% by 2015 compared to the no-measures-implemented base case.

Improved vehicle management

New information technology makes possible better logistics systems. GPS units in the vehicles provide complete information to traffic managers regarding the vehicle locations; this information can be supplemented with information on load to load capacity ratio. This is valuable information for traffic managers. In addition, itinerary scheduling programs can be used to optimize more complicated logistics systems. Projects carried out by various companies show that savings of 10-15% of the total driving distance are possible through the use of IT systems (Swahn, 2007). Schenker Consulting puts the potential at 5–10% (Ljungren, 2007). Partial load goods shipped less than 100 km offer the largest savings with this kind of system. Assuming efficiency gains of 10%, and correcting for voluminous freight type, the potential emissions reductions are 0.6%.

Eco-driving

Eco-driving offers a relatively large potential for fuel savings. However, a number of measures need to be in place to ensure driving in the long-term is more fuel efficient. Eco-driving training has demonstrated that fuel savings of 10-20% are possible, but longer-term monitoring has shown that over the long-term savings are closer to 3-6% (SRA, 2004). With eco-driving feedback systems, higher savings are possible longer-term, too. Lackéus (2007) estimates that for long-distance traffic, savings amount to 6-12%, while for deliveries the figure is somewhat higher, 9-15%. These systems are more effective if combined with additional driver development and incentives. Results from the spar-coach (Eco-coach) program which includes incentives and follow-up measures point to savings for trucks by 2-12% (Jonsson-Rynbäck, 2007).

One part of eco-driving is observing the speed limit. This could be simplified by setting speed regulators to 84 km/h instead of 89 km/h. On roads marked 90km/h, 70% of tractor trailer vehicles maintain speeds that are on average 6 km/h above the limit. On roads marked 110 km/h, 87% of these vehicles maintain speeds that are on average 7.5 km/h too high (SRACS, 2005).

We have in mind a scenario in which the speed regulator is set lower, which in and of itself saves 2% on fuel, that all vehicles are required to have eco-driving feedback systems by 2015, and that trucking companies implement eco-driving training, continued development, and incentives programs. In Sweden, 16,000 drivers have already received eco-driving training. However, the training is only one small part of the potential for savings from eco-driving. We estimate 20% of the full potential has been utilized. Based on this, the total potential for savings from eco-driving amounts to 5.2%, by 2015.

Road trains

Current regulations in Sweden and Finland allow for longer and heavier trucks than are permitted in the rest of the EU. Trucks carrying packaged goods loads rarely utilize their full weight capacity since the freight is relatively light relative to volume. Should vehicles with additional trailers, so-called road trains, but still within the weight limit, be allowed on certain roads with no oncoming traffic, this would reduce the number of trucks on the road. The main roads of interest are the highways between major cities. According to estimates in 2001, 40% of the transportation work by road takes place on routes between major cities (based on SIKA, 2005a). Partial load goods constitute ca 41% of freight by road, and about 40% of this may potentially be carried by road trains. In the ideal scenario, adding another trailer would reduce the number of trucks by 30%. If we assume a 15% increase in fuel consumption, this amounts to fuel savings of 2.7%.

4.1.3 MORE EFFICIENT VEHICLES

Improved fuel economy

There are three main ways of improving a vehicle's fuel economy: reduce the air resistance, reduce the rolling resistance, and improve the efficiency of the combustion engine. Muster (2000) estimates the potential for efficiency improvements from 2000 to 2020 for trucks weighing 40 tons. Air resistance reductions can yield 10% fuel use savings; with rolling resistance improvements, the number is 22%. Adding more efficient engines adds up to 32%. Volvo estimates fuel efficiency improvements of 15% from now until 2020 (Mårtensson, 2006). If we take into account the improvements Volvo has already made to date, but use Muster's numbers, the potential from 2006 to 2020 can be put at 19%. Thus, Muster's and Volvo's results are consistent. We assume that vehicles sold between 2010 and 2015 are 10% more efficient than today's vehicles. Taking fleet turnover into account, this amounts to a reduction of emissions by 4.8% by 2015.

Hybrid trucks

Between now and 2015, hybrid trucks for distribution traffic (deliveries) will be brought to market. Volvo will introduce a hybrid truck in 2009. In city traffic, hybrid trucks use 25% less fuel. Assuming that 20% (on the high end of estimates) of all delivery trucks sold are hybrids, starting in 2010, this would amount to a 0.3% reduction in emissions by 2015.

4.1.4 NEW FUELS

Blending FAME as well as hydrogenated oils

Until August 2006, only up to 2% FAME could be blended in diesel according to the Swedish MK1 standard; today up to 5% is allowed. In the EU, work is underway to determine whether 10% could be allowed.

New technology also permits removing oxygen from vegetable oils by adding hydrogen, so-called hydrogenation. This results in so-called green diesel, a fuel very similar to conventional diesel, but based on biomass. Preliminary analyses indicate that greenhouse gas emissions are lower for hydrogenated oils than for FAME and that costs are lower, too (UOP, 2005). However, FAME and green diesel compete for the same feedstocks, and the supply of these is fairly limited, as shown in section 3.2.3.

An optimistic assumption would put FAME and hydrogenated oils at 10% of diesel in 2015. This requires considerable imports and that global competition for oils is not too great. Greenhouse gas emissions result from FAME and hydrogenated oils at both the cultivation and processing stage. Emissions for RME, currently the most common FAME, from cultivation, processing, and transportation are roughly 50 g CO_2-eq/MJ, compared to 14 g CO_2/MJ for extraction and refining plus 73 g CO_2/MJ upon combustion, for diesel (Concawe, 2006). Increasing the amount blended in diesel from 2 to 10% reduces greenhouse gas pollutants by 4.6%.

Biogas

Biogas is produced from organic materials such as manure or waste through fermentation. 10% of biogas produced in Sweden is upgraded to pure methane and used as transportation fuel (Eriksson and Olsson, 2007). In 2005, biogas accounted for 0.2% of Swedish transportation fuel (STEM, 2006). Biogas is mainly used for buses on local routes; some is used in garbage trucks, taxis, and passenger vehicles. In cities where the biogas distribution infrastructure is in place, some of the local deliveries could run on biogas. The production of biogas has been fairly constant in the past five years (Eriksson and Olsson, 2007), but if we assume that the number of trucks running on biogas doubles by 2015 and take into account emissions from biogas production, 37 g CO_2-eq/MJ (Concawe, 2006), this yields savings of 0.03% by 2015.

4.2 POTENTIAL BY 2025-2030

Several of the measures we have discussed will not have met their full potential by 2015. It will take time to develop and implement new technologies. To obtain a rough estimate of the potential, we calculate how much emissions could be reduced by 2025-2030. The reductions should not be thought of as reductions from a current baseline, but from a base case business-as-usual scenario in which no measures are implemented. In the real world, if no measures are implemented, we can expect emissions to increase by 50-80% by 2030. The calculations should be considered sign posts, since the uncertainty increases significantly with the longer time-frame.

4.2.1 MORE EFFICIENT SHIPMENTS

It is hard to estimate the long-term potential for more efficient shipments. New systems may very well be developed during this period and the incentives for co-loading may increase. Perhaps the estimated 2015 potential for mass freight transportation will double by 2025-2030. We assumed that 40% of the relevant freight would have been shifted to road trains by 2015. The trend is toward a greater share of partial load goods, which means that we can estimate the potential as 25% greater in the long run. As to eco-driving, this potential must be considered fully utilized by 2015.

4.2.2 MORE EFFICIENT VEHICLES

The trend toward reduced resistance and more efficient engines will most likely continue until 2030; in addition hybrid technology will have had time to catch on more.

Volvo estimates that trucks will be 15% more efficient in 2020. We can assume these represent the entire fleet in 2025-2030; in addition new vehicles with even higher efficiencies will probably be introduced. We can estimate the fleet as a whole is 20% more efficient than today. Development and expansion of hybrid technology will yield further improvements. Hybrid technology holds the greatest promise in city traffic, but emissions savings of up to 5% are achievable on the highway (Muster, 2000; Truckinginfo, 2007). Assuming that all delivery vehicles and half of long-distance trucks are hybrids 2025-2030, this would entail carbon dioxide savings of ca 5%.

4.2.3 NEW FUELS

During this period, the amount of FAME and hydrogenated oils will likely be limited by the supply of resources, particularly if climate policy leads to an increase in demand in other areas, too. For this reason, we assume FAME and hydrogenated oils will continue to be blended into diesel at 10%.

Several demonstration projects are underway aiming to make biomass gasification and syngas purification work large-scale. In the best case scenario, the technology will be available for large-scale applications by 2012. At that point, biomass could be used to produce DME and Fischer-Tropsch-diesel (FTD) or hydrogen which could be used in refineries.

The first large-scale plants for DME or FTD will likely involve gasification of black liquor because costs are relatively low. By 2030, there may very well be plants using woody biomass. Emissions from DME or FTD production are 5 g CO_2-eq/MJ fuel if energy inputs are from biomass (Concawe, 2006).

Three factors will limit bioenergy between now and 2030: how quickly technology develops, how quickly industry dares construct large-scale plants based on untested technology, and the competition for bioenergy. The Commission on Oil Independence (2006) suggested that by 2020 we should be producing 12-14TWh biofuels. Together with the total potential indicated in section 3.2.3, this provides an optimistic estimate that we in 2025-2030 have 15 TWh diesel fuel from black liquor and gasified cellulose. This includes DME for special vehicles as well as FTD blended in regular diesel. This amounts to 25% of all diesel in 2025 (STEM, 2007a). However, more emissions could be reduced at less cost if the corresponding feedstocks were used for heat or power.

To produce diesel, refineries require hydrogen. Currently, propane is used to produce hydrogen, but other solutions are possible. If natural gas is used, total emissions from diesel are cut by 1.3% (Sjöberg, 2007). Bioenergy gasified along with pet coke could be used as a hydrogen source in the future. The savings would depend on how much coke is used compared to biomass, and there are still no detailed plans for this technology. If we assume 75% biomass, emissions savings will be 3.5%. This technology may be applicable for half the Swedish diesel production in 2025-2030. Carbon dioxide emissions from processing can potentially be sequestered since these are relatively easy to separate. Because the carbon dioxide derives from biomass, this would reduce emissions by 7-8% (Azar, et al 2006).

Biogas amounts are so small that we do not conduct a separate analysis for this. Competition with mass transportation and passenger vehicles makes it hard to estimate how much biogas might be used for local freight deliveries.

4.3 RESULTS

Table 1 summarizes the results. The first column indicates the emissions reductions for the ton-km to which a certain measure applies. Biogas, DME, and FTD result in the largest reductions.

Measure	Reduction per relevant ton-km	Potential by 2015	Long-term potential
Efficient shipments			
Mass freight transportation	20 %	0.3 %	0.6 %
Improve logistics	10 %	0.6 %	1.2 %
Eco-driving	6.5 %	5.3 %	5.3 %
Road trains	23 %	2,7 %	4 %
Efficient vehicles			
Improve fuel economy	10 %	4.8 %	20 %
Hybrids	25 %	0.3 %	5 %
New fuels			
FAME and hyrogenated oils	4.6 %	4.6 %	4.6 %
Biogas	41 %	0.03 %	0.03 %
Biomass for hydrogen in refineries	1.8 %		1.8 %
DME and Fischer-Tropsch-diesel	23 %		23 %

Table 1. Emissions reduction potential by individual measure implemented.

Logistics solutions come next; they can have a large impact on the relevant freight.

The next column, potential by 2015, shows estimates of how much total emissions from freight transportation by road could be reduced by 2015. In some cases the difference between a measure's effect on ton-km and effect on total emissions is large. This happens when a measure is relevant to only a small part of the total flow of freight.

The long-term potential indicates how much emissions could be reduced in the long run, 2025-2030. These estimates have much greater uncertainty. If all the long-range measures were to be implemented, emissions could reduce by half compared to the base case.

4.3.1 STRATEGIC PERSPECTIVE

In order to reach climate neutral freight transportation in the long run, these measures should not be considered only in terms of short-range reductions, but also in terms of long-range changes such as technology and infrastructure.

Logistics solutions and eco-driving will contribute to a more efficient transportation system in the long run, entirely in line with the long-term vision. The problem associated with these measures is that they reduce the cost of shipping by road which may lead to an increased transportation demand in general and shift freight from sea or rail to road, which would increase emissions. This should not be seen as an argument against efficiency improvements. Rather, all transportation modes should pay for their environmental impacts to achieve fair competition.

Developing the combustion engine further may appear like a dead-end, if fuel cells are the future. But as seen in section 3.1, hydrogen does not seem like the solution for long-distance shipping. If we instead imagine a future with biofuels, improving engine efficiency leads down the road toward future climate neutral freight transportation. Hybrid technology can also be used in conjunction with biofuels or fuel cells.

Blending FAME or hydrogenated oils results in reduced emissions in the short run, but the potential is too small for this to amount to anything major in the future. Expansion will most likely be limited by resource availability; therefore there is a risk of lock-in (Maréchal, 2007). That is, moving ahead on FAME could preclude other initiatives focusing on more efficient fuels since FAME would be first to market and dominant. In order not to delay second-generation fuels based on gasified cellulose, major efforts to develop this technology are required.

Using the hydrogen produced by gasified biomass in refineries could be a way of developing gasification technology without going all the way to renewable fuels. This would be a win-win situation by simultaneously making conventional diesel somewhat green and developing a strategic technology. The road to climate neutral freight transportation will have to go via significant efforts to make gasification of biomass work and via synthesizing the syngas to create a fuel for freight vehicles.

4.4 SCENARIO FROM NOW UNTIL 2015

Were all the measures to be implemented by 2015, this would result in a reduction of emissions compared to a base case with no action.

SIKA has made projections for freight transportation until 2020 (SIKA, 2005a). However, these include shipments run by non-domestic transportation companies. The current report mainly concerns measures affecting Swedish transportation companies, trucks, and transportation fuels commerce. For this reason, we only consider domestic traffic involving Swedish trucks. As we have seen, freight transportation has grown in step with the economy as a whole, and emissions per ton-km have been fairly constant the past five years. We estimate economic growth at 2.5% and assume that CO_2 emissions per ton-km remain constant. This yields an increase in transportation work from 35,000 million ton-km in 2005 to 44,000 million ton-km in 2015. During the same period, carbon dioxide emissions from freight traffic will increase from 3.8 to 4.8 million tons.

In order to see the total potential for emission reductions, the percentages in table 1 cannot simply be added. Rather, efficiency improvements should be multiplied to yield the total potential. Calculations show that if all the measures are implemented, the reductions almost cancel the expected growth in emissions by 2015, see figure 8. The reductions are fairly evenly distributed over the truck categories, heavy, medium, and light. Certain measures, such as improved vehicle management and mass freight transportation mainly pertain to lighter trucks, while road trains mainly affect heavy trucks. Improvements in vehicle efficiency and renewable fuels affect light and heavy traffic equally.

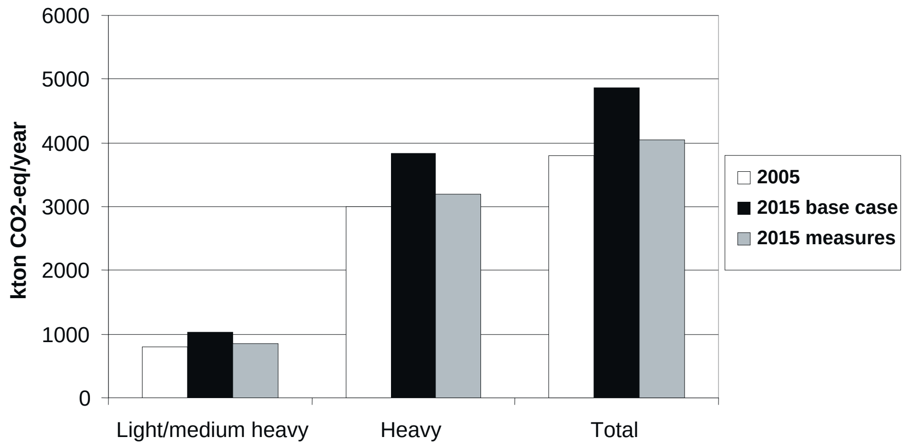

Figure 8. Scenarios for carbon dioxide emissions until 2015 for heavy traffic (trucks over 32 tons) and light and medium traffic (trucks under 32 tons).

4.5 POLICY MEASURES

Carbon dioxide reductions rarely happen on their own; often, it is less expensive to pollute more rather than less. Therefore, we urgently need policy instruments that put a high price on carbon dioxide. In Sweden, we have had a carbon dioxide tax on transportation fuel since 1990; raising that tax would provide support for all the measures considered here.

In order for biofuels to be competitive, additional policy measures will have to be implemented. Today, biofuels are not subject to a carbon dioxide tax or energy tax. The current government has promised to maintain this tax-free status until 2013. Low blend diesel requirements are also possible. For higher percentages of FAME, diesel fuel specifications have to be changed and diesel engine modifications may be required. Climate certification of biofuels could also provide support.

A per-kilometer tax is another possibility. Depending on how it is constructed, it could promote more efficient vehicles, but it will mainly incentivize more efficient logistics and reduce the demand for transportation.

Changes in certain regulations could also substantially affect emission reductions. Lowering the speed regulator, requiring eco-driving feedback information systems, and supporting eco-driving training can probably realize the emissions reduction potential from changes in driving habits. Road trains are not allowed today; this requires changes in legislation. Mass freight transportation can be supported further by preferred treatment in city traffic.

The EU has agreed to reduce average carbon dioxide emissions from new passenger cars. However, it is not clear that this non-binding agreement will be respected; introducing an actual required standard instead has been proposed (European Commission, 2007). A similar solution could work for trucks: CO_2/km must stay below a given limit for a given truck size. This will require standardized EU fuel cycles, which currently do not exist.

4.6 DISCUSSION

The Swedish Energy Agency estimates that carbon dioxide emissions from freight transportation as a whole can be reduced by 2.5 million tons by 2020 (STEM, 2007a), compared to the base case. The current report instead points to 0.8 million tons by 2015. There are several reasons for this difference. By 2020, the effect of more measures will have kicked in, and the base case numbers are also higher. In addition, the estimate pertains to the entire freight sector, i.e., rail and sea as well as road which means that the potential for measures is greater. The estimate also assumes that demand will be modified by higher prices.

A dampened demand is based on two phenomena: companies will demand fewer shipments if costs are higher, and a number of small logistics improvements will be made when costs are higher. However, these are hard to estimate since they cannot be accumulated in one single measure. International studies show that freight transportation demand has a price elasticity between -0.5 and -1.5 (Graham and Glaister, 2004). If the price of transportation increases by 1%, transportation work will go down over time, by 0.5 to 1.5%.

Thus, in order to reduce emissions by an additional 0.4 million tons through logistics and reduced demand, fuel prices would have to increase by about 50% corresponding to a tax of roughly SEK 0.25/km (assuming an elasticity of -1).

With a broader approach that also included effects on demand and transportation mode shifts, the estimate of potential emissions reductions would have been higher. However, the estimate provided in this report is not based on a cost-efficiency perspective. The economic cost-efficiency of the various measures most likely varies widely. Our purpose has been to map the long-term road to climate neutral freight transportation.

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