FUEL SAVINGS FOR HEAVY-DUTY VEHICLES
”HDEnergy”
Summary report 2003 - 2005

Authors

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### Abstract

In the years 2003 – 2005 VTT Processes carried out an extensive research program. The project aimed at reducing the energy consumption of heavy-duty vehicles. The goal of the research program was to achieve a permanent fuel saving of 5-10%. Six research parties and some 20 sponsors took part in the project.

The research program included altogether 12 technical sub-projects. The themes for the sub-projects were broken up into vehicle technology and transport system research. Themes for research were among others the specific fuel consumption of different types of vehicles, modelling the fuel consumption of vehicles, technical aids for the driver, minimising the rolling resistance of tires, the impact of the road surface on the tires’ rolling resistance, lubricants, the influence of maintenance and after-market equipment on fuel consumption, transport business monitoring systems, eco-driving of heavy-duty vehicles, and automated load detection for trucks.

The results from the years 2003 – 2005 indicate that significant savings in fuel consumption can be reached by many independent technical improvements. The potential savings of different technical measures were evaluated as follows; the weight and aerodynamics of the vehicle up to 30%, guidance of the driver by technical aids 5 – 15%, variation between different vehicle makes 5 – 15%, tires 5 – 15%, different air deflectors 4 – 8%, type of trailer 3 – 5%, and lubricants 1 – 2%. The fuel consumption of a heavy-duty vehicle under dynamic driving conditions is however primarily determined by the weight of the vehicle and the driving-cycle. Under preliminary tests in 2005, it could be demonstrated that a driver’s aid suited for buses, an automated load detection system for trucks and an automated detection system for slippery road surfaces, all developed under the project, worked.

The project has got its own web page in connection with Motiva Oy’s web pages at [www.motiva.fi/raskaskalusto](http://www.motiva.fi/raskaskalusto). A complete report-archive can be found at the web pages.

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PREFACE

This report is a summary report of the “Fuel savings for heavy-duty vehicles (by vehicle technology and transport system solutions)” project, which was carried out in the years 2003 – 2005. The project was rather extensive, including altogether 12 technical sub-projects. Some of the sub-projects have their own reports. The main project has got three additional annual reports. Separate brochures have been made for the sub-projects.

During the years 2003 – 2005 the project had altogether 19 sponsors, including VTT. One sponsor, although, took part only in year 2003. The biggest sponsors were Tekes – Finnish Funding Agency for Technology and Innovation and AKE - the Finnish Vehicle Administration. Six research parties took part in the implementation of the project. They were: VTT Processes, VTT Buildings and Transport, Helsinki University of Technology – Laboratory of Automotive Engineering, Tampere University of Technology - Institute of Transportation Engineering, Helsinki Polytechnic Stadia and Motiva Oy.

This summary report briefly presents the project itself and its most important accomplishments.

VTT would like to thank all the participants of the project, including companies who provided the project with equipment and technical expertise.

Espoo 27.3.2006

Nils-Olof Nylund

Coordinator of the project
1 BACKGROUND, GOALS AND CONTENT OF THE PROJECT

A notable part of the Finnish public transportation, roughly 60% of the passenger kilometres, is handled by buses. The truck traffic as well plays an important role in the haulage of commodities within the borders of Finland. About 75% of all haulage is carried out by trucks. The significance of heavy-duty vehicles on our society is vast.

The use of transportation fuels in Finland in year 2005 was 3.9 million tonnes. Out of these 3.9 million tonnes, 1.9 million tonnes were petrol and the remaining 2.0 million tonnes diesel fuel. (ÖKKL 2006) Heavy-duty vehicles account for roughly 80% of the total consumption of diesel fuels, in other words about 1.6 million tonnes or 1,900 million litres. Every percentage unit of diesel fuel that can be saved by heavy-duty vehicles will therefore amount to annual savings of 20 million Euros (with current fuel prices including tax). The price of fuel kept rising strongly in year 2005. One litre of diesel fuel, including tax, came by the end of year 2005 to around 1 Euro.

One can assume that the transport service producers as well as the end users of these services, strive for an as efficient use of vehicles and generation of services as possible. To this extent heavy-duty traffic differs from passenger car traffic. Despite this fact, there is still potential within the heavy-duty traffic to make further savings.

Fuel can be saved by technical means, by for instance:

- choosing the right vehicle for different types of tasks
- technical improvements to the vehicle and its components
- optimising the use of fuel and lubricants
- optimising the use of vehicles, that is by utilizing various information systems

In addition to engineering, also the driver affects the fuel consumption significantly. A poor driver can easily consume up to 30% more fuel than a skilled driver. There are although various training programs available for drivers.

Figure 1 is an example of how fuel saving can be approached from a vehicle technology perspective. The picture shows energy usage and fuel economy of a heavy semi-trailer combination truck (gross weight 36 tonnes) when driving at a speed of 104 km/h (allowable in the U.S.). The picture is taken from the 21st Century Truck Program. Both the present situation and well the target of the program can be seen from the picture. The goal of the program, fuel savings of up to 35%, is a very challenging one (21st Century Truck 2000). Figure 2 shows, based on Figure 1, the relative distribution of energy use under present circumstances.

When fuel power is 400 kW, the mechanical work produced by the engine is 160 kW (efficiency 40%). The figure of 160 kW is equivalent to the sum of the actual tractive
resistances (air- and rolling resistance), losses in the power line and the power needed by the technical aids. When driving at, for instance a speed of 104 km/h, 53% of the produced mechanical work is needed for overcoming the air resistance and 32% for overcoming the rolling resistance (when driving on flat land).

The largest relative improvements are pursued within the power needed by auxiliaries (-50%) and rolling resistance (-40%). When it comes to the efficiency of the engine, a relative improvement of 10% is pursued. The absolute losses of the engine would however be reduced by 40%, since due to the other measures the need for power would decrease.

If the power needed by the auxiliaries would be halved, while other factors would remain unchanged, a fuel saving of roughly 5% would be achieved. If respectively the transmission losses would be halved, a saving in fuel of a short 3% would be achieved. Thus one can conclude, that in order to reach big absolute changes the measures should primarily be focused on lowering both the air- and rolling resistance and improving the efficiency of the engine.

On the other hand, a sheer reduction in driving speed from 104 km/h to 80 km/h would lower the need for power and fuel by 40% (see Figure 6). When changes in speed come along, the mass of the vehicle becomes the decisive factor. The power needed for accelerating the vehicle always depends on the mass of the vehicle. Kinetic energy always goes to waste when reducing speed by braking.

In 2002 Tekes issued a call for projects on the subject of “Technology and business activity for managing the climate change”. In the quest was among others mentioned innovative solutions for fuel savings in different energy using sectors, including transportation.
VTT responded to this quest by planning an extensive three year project comprising several research parties and sponsors. The goal of the project ("HDEnergy") was to lower the fuel consumption of heavy-duty vehicles. Tekes made the decision to finance the project and it was launched in the spring of 2003. In addition to research parties, producers and buyers of transport services and companies producing both vehicle components and information systems, participated in the project. Research parties that took part in the project were VTT Processes (abbreviation VTT PRO), VTT Buildings and Transport (abbreviation VTT RTE, since the beginning of 2006 VTT does not any longer have individual research institutes), Helsinki University of Technology – Laboratory of Automotive Engineering (HUT), Tampere University of Technology - Institute of Transportation Engineering (TUT), Helsinki Polytechnic Stadia and Motiva Oy.

The project had altogether 19 sponsors during the years 2003 – 2005, including VTT. One sponsor, although, took part only in year 2003 (Appendix 1). The biggest sponsors were Tekes – Finnish Funding Agency for Technology and Innovation and AKE - the Finnish Vehicle Administration. The annual budget of the project was some 600,000 Euros, which makes the total budget some 1.8 million Euros.

Captured, the goal of the research program was to develop heavy-duty vehicles, their components and systems controlling the vehicles in order to prepare the way for a permanent fuel saving of 5-10% (Figure 3). When considering the results of the project, one can disclose that the target set is easily within reach merely by technical measures.

Experimental studies with both buses and trucks were made within the project. The versatile heavy-duty vehicle laboratory at VTT, introduced early 2002, played a major role in the project. The equipment includes, among others, a heavy chassis dynamometer teststand which can be used to charge heavy-duty vehicles in order to simulate different real-life driving patterns and different load-circumstances. The use of the vehicle (the driver) has a great impact on fuel economy. Therefore technical aids for guiding the driver into a more fuel efficient driving style were included into the project.
Fourteen (14) sub-projects were constituted into the project (implementing party in brackets), of which 12 were technical subject matters.

1. Coordination (VTT PRO, TEC TransEnergy Consulting Ltd)

Vehicle Technology

2. Development of test methods (VTT PRO)
3. Specific fuel consumption of different types of vehicles (VTT PRO)
4. Modelling the fuel consumption of vehicles/modelling of the driver (HUT)
5. Development of a driver’s aid device for buses (VTT PRO, VTT RTE, HUT)
6. Energy efficiency of tyres (HUT)
7. The impact of the road surface on rolling resistance (HUT)
8. Fuel and lubricant technology for improved fuel economy (VTT PRO)
9. Maintaining, updating and retrofitting of vehicles (VTT PRO)
10. Automated load detection for trucks (VTT RTE, VTT PRO)

Transport System Research

11. Development of a fuel- and environment tracking system (VTT RTE, VTT PRO)
12. Creating follow-up systems for vehicles (TUT)
13. Optimal driving style for heavy-duty vehicles (VTT RTE)

14. Training and dissemination (Motiva Oy)
2 PRIMARY ACHIEVEMENTS OF THE PROJECT

One of the most significant achievements of the project was perhaps the collaboration between transport companies, sponsors, the authorities and research institutes.

Owing to the project, an ongoing process for improving fuel efficiency was brought about. Methods for verifying fuel savings were also introduced. A new triennial project covering the years 2006-2008, named “Heavy-duty vehicles: Safety, environmental impacts and new technology”, has been set in motion.

The project was kind of a miniature research programme, yet large enough to its volume in order to get visibility and carry weight. The project cooperated closely with the general fuel savings programme for the trucking sector delivering e.g. measured data for the use of that programme.

Due to the extent of the project, it was possible to moderately invest in communications. Comprehensive web pages for the project were created on Motiva Oy’s servers at www.motiva.fi/raskaskalusto. The web pages contain, among other, a complete report-archive. The project also produced printed communication material, a brochure describing the project as a whole and brochures for the most important sub-projects. An example of a score-card can be seen in Figure 4.

![Figure 4. An example of a sub-project score-card (downloadable at www.motiva.fi/raskaskalusto).]
The project defined potential savings that can be achieved by technical measures, e.g.:

- the weight and aerodynamics of the vehicle up to 30%
- driver’s guidance by technical aids 5 – 15%
- variation between different vehicle makes 5 – 15%
- tires 5 – 15%
- air deflector’s effect 4 – 8%
- type of trailer 3 – 5%
- lubricants 1 – 2%

Some parts of the results can be put to use mainly when acquiring new vehicles, but some even when maintaining the current vehicles. One can conclude from the figures, that an average 5 – 10% saving in fuel economy can be achieved reasonably easy, of course depending on the initial stage.

The project also functioned as a platform for innovations. Inspired by the project, Kabus Oy launched a hybrid-bus development project which advances as an enterprise research project, sponsored by Tekes. Furthermore, the umbrella project produced three new information-technology related innovations, which all will be brought into play during the next research phase:

- driver’s air for buses
- automated load detection for trucks
- automated slipperiness detection

Good results were also attained in transport system research. The pre-study for “Development of a fuel- and environment tracking system” lead to the implementation of EMISTRA (Energy and Environmental Accounting and Reporting System for Transport and Logistics Sector) www.emistra.fi. An indexation system for evaluating the driver’s performance was created in another system-related project.

Examples and findings from the years 2003 – 2005 of those achievements of most concern are presented, subproject by subproject, in the following.

**Development of test methods**

- accreditation for emission- and fuel economy measurement for heavy-duty vehicles in the chassis dynamometer test-stand
- development of measuring methods depicting typical load patterns for buses (urban buses and long distance buses) and trucks
- development of a method for simulating the road gradient (topography) in the chassis dynamometer test-stand
- a system for determining the tractive resistance of a vehicle based on coast-down tests
- development of a method for measuring the tractive force of a trailer based on the measurement of the forces in the coupling between tractor and trailer
- development of a method to read the CAN data-bus which data is to be used in chassis dynamometer and on-the-road measurements
Specific fuel consumption of different types of vehicles
- created reliable tractive resistance values for different types of trucks and buses
- measured the actual need for power in different types of vehicles
- disclosed how, by lightening the vehicle and improving its aero-dynamical features, it is possible to lower the tractive resistance by some 25% and thereby reduce fuel consumption by over 30%
  - example: Kabus full-aluminium bus with downsized engine
- produced a broad series of measurements for Euro 3 trucks and the first measurements for new Euro 4 trucks
  - difference between vehicle makes in fuel consumption up to 15%
  - the Euro 4-technology did not remarkably increase fuel consumption, based on the measurements of two vehicles (± 2 %)
- demonstrated the impact of the type of trailer (full trailer, 4 vs. 5 axles) on fuel consumption (reduction of 3 – 5%)
- demonstrated the impact of air deflectors on fuel consumption (reduction of 4 – 8%)
- researched the difference between two parallel engine types and transmissions (manual and automatic) in an engine test stand
  - in the comparison the engine with lower power rating was more fuel efficient
  - when driving with low load, losses caused by the automatic transmission were notable

Modelling the fuel consumption of vehicles
- developed a functional model for simulating buses
  - for a bus with automatic transmission, the simulated results were between 95 and 113% of the measured values
  - through simulation the effect of, for instance, accessories and different power train types can be estimated on fuel consumption
- a model for changing gears with a manual transmission was created
  - estimated the impact of different gear shifting strategies on fuel consumption in trucks with manual transmission
- modelled the effect of driving styles on fuel consumption in urban buses
  - based on calculations, the savings potential is some 15%

Development of a driver’s aid for buses
- developed and demonstrated a working prototype of a driver’s aid
- guidance is bound to the route and schedule
- in the first measurements the fuel consumption, even for an experienced driver, decreased by some 5%, the estimated savings potential is although 10 – 15%
- both running on time and safety (less speeding) were improved

Minimising the rolling resistance of tyres
- developed a methodology for research of tyres both on freeways and on roller type test-stands
- variation between different tyres was at its most up to 15%, generally due to differences in patterning and harshness
confirmed that the super-single solution does not give remarkable fuel savings compared to a normal twin wheel mounting

- a worn-out tyre has a lower rolling resistance than a new tyre, but is also more unsafe, the patterning also affects the rolling resistance
- re-grooving of a tyre is gainful from a fuel economy perspective, hence the life span of the tyre can be extended while the tyre is at its most fuel economic phase

The impact of the road surface on the tyre’s rolling resistance
- determined the suitability of two measuring trailers for studying the impact of the road’s surface
  - absolute rolling resistance forces could not be measured, but measurements and discoveries that were made during the tests give a good basis for designing a new type of measuring trailer

Fuel and lubricant technology for improved fuel economy
- choosing the right engine oil lowers the fuel consumption
  - savings potential 1 – 3%, depending on the engine type and load profile
- differences in fuel consumption caused by power transmission oils are at most 0.5%, when driving under warm weather conditions
  - differences between the oils are emphasised in cold conditions
- the quality of fuel clearly affects the engine power and fuel consumption
  - compared with winter quality fuel, summer quality fuel gives about 5% more power and a 3.5% lower volumetric fuel consumption

Maintaining, updating and retrofitting of vehicles
- a bus-engine that had been driven 700,000 km was reconditioned in stages
  - the reconditioning measures did not much affect the engine’s performance characteristics, which shows that a high mileage engine can be in very good condition
- a retrofitted Volvo VEC – emission control system transformed a Euro 2 class engine’s emissions near to the emission levels of a Euro 5 engine
- five commercial technologies for decreasing fuel consumption were researched
  - a detergent for blending into fuel, a detergent for blending into engine oil, technologies based upon magnetism, an agent for coating metal and blending air into the fuel
  - none of the researched technologies lowered the fuel consumption

Automated load detection for trucks
- the concepts of automatic slipperiness control and automated load detection were proved to be functional in preliminary on-road tests
  - the automated load detection system is based on monitoring power data from the vehicle’s CAN data bus and on continuous calculations of its motion balance (kinetic and potential energy)
  - based on preliminary measurements, an algorithm capable of identifying the vehicles load with an accuracy of about 5% was developed (the accuracy should be improved in the future)
Development of a transport business fuel- and environment tracking system
• the EMISTRA pilot project started as a separate project based on a pre-study within the project
  o the pre-study was completed in January 2005
  o a web-based system is in use

Creating follow-up systems for vehicles
• a pilot system project of four companies was carried out mainly as planned
  o the basic idea is a programmable data-logger, which makes use of CAN and GPS data
  o detailed information of both buses and trucks was produced
  o an indexation-system for depicting the driver’s driving style was created

Optimal driving style for heavy-duty vehicles
• for both buses and trucks, changes in kinetic energy are essential for fuel economy
• economical and uneconomical driving styles for buses have been identified
  o the results were put to use when creating the driver’s aid for buses
• three driving-cycles describing the bus traffic in the Helsinki metropolitan area were created
  o the engine load was analysed in different driving situations
• in year 2005 the study was extended to trucks by studying data which had been gathered earlier
  o optimising the driving of trucks is challenging, since their routes are far less constant than those of buses and besides, the gradient of the road affects fuel economy significantly

The project also produced five theses:

• Efficiency and safety of bus tyres
  o thesis of Tommi Mutanen 2003, HUT, MSc

• Lubricants effect on losses in the transmission of heavy-duty vehicles
  o thesis Riku Mäkelä 2005, Stadia, BSc

• Updating and maintenance of a bus engine’s performance characteristics
  o thesis of Mika Niemelä 2005, HUT, MSc

• Simulation of driver behaviour influence on fuel consumption
  o thesis of Antti Lajunen 2005, HUT, MSc

• Tyre rolling resistance on road
  o thesis of Antti Leinonen 2005, HUT, MSc
3 EXAMPLES OF RESULTS FROM THE SUB-PROJECTS

The examples are based upon results which are presented in the annual reports of 2003, 2004 and 2005. In this report the results are introduced in a condensed manner. The authors of the original texts come out in the annual reports and those responsible for the sub-projects in Chapter 1. The report list is presented in Appendix 2.

Some parts of the tasks are clearly interlinked. This can best be seen in the development work of the driver’s aid device. Three research parties, HUT, VTT PRO and VTT RTE, participated in the creation, definition and realisation of the equipment.

3.1 DEVELOPMENT OF TEST METHODS

General

There are no official methods for measuring the fuel consumption or emissions for entire heavy-duty vehicles. The official type approvals for engines are done in engine dynamometers, without taking into account the vehicles features or purpose of use.

In lack of recognised European measurement methods, VTT started developing its own method for measuring heavy-duty vehicles on a chassis dynamometer. VTT also applied for accreditation of its method. Methods for measuring emissions and fuel consumption of passenger cars on chassis dynamometers already exist. The methods describe the general principles of measuring vehicles on a chassis dynamometer. The official emission certification measurements for heavy-duty vehicles are made as engine tests. The Directives 1999/96/EC and 2005/55/EC describe the so called ETC – European Transient Cycle, in which emission measures are made using a full-flow CVS dilution tunnel. ETC – testing is required for all engines since the Euro 4 - standard. Similar measurement methods can also be used in dynamic vehicle measurements.

The American Society of Automotive Engineers – SAE has published a code of praxis for chassis dynamometer measurements of heavy-duty vehicles, SAE J2711: Recommended Practice for Measuring Fuel Economy and Emissions of Hybrid-Electric and Conventional Heavy-Duty Vehicles. Furthermore, the US Environmental Protection Agency – EPA has defined the Urban Dynamometer Driving Cycle UDDS – to be used for heavy-duty vehicles on roller type test-stands. (DieselNet a)

The measuring method developed at VTT, which includes emission and fuel economy measuring, is based upon the above-mentioned methods and recommendations along with the safety regulations for measurements on the chassis dynamometer (Figure 5). For buses, VTT primarily uses the German Braunschweig urban driving-cycle. (DieselNet b)
VTT prepared a definite code of practice for the measurements and applied for accreditation of the measurements. The Finnish Centre for Metrology and Accreditation – MIKES audited the measurements and granted accreditation for the measurements in June 2003 (MIKES T125: In-house method, VTT Code MK02E).

The need for data on actual vehicle fuel economy is grand. During procurement of vehicles, it is virtually impossible to compare the fuel economy. This is because the data provided by the manufacturers differ from each other drastically. The impact of the buying decision can be seen through the vehicle’s whole life span; therefore the outcome of the decision cannot be undervalued. In order to calculate the actual impact on the environment, the true values for fuel economy and emissions are needed, which vary under different driving circumstances with different vehicles and workloads. Standardised procedures also prepare the way for measuring the actual impact of, for instance, lubricants, tyres, auxiliary devices and transmission settings in tests comparable to actual driving.

The fuel consumption for the complete vehicle in an actual driving situation depends on, not only the engine’s efficiency, but also on the weight of the vehicle, the tractive resistances, technical solutions and the driving profile.

![Figure 5. The structure of VTT’s method for heavy-duty vehicle chassis dynamometer measurements.](image)

**The chassis dynamometer and tractive resistances for heavy-duty vehicles**

VTT has got a chassis dynamometer test-stand for measuring complete vehicles. Real life driving situations can be simulated on the test stand by emulating the vehicle’s tractive resistances and driving route. This way the effect of, for instance, the engine, transmission, final drive and auxiliary devices can be taken into account. The influence of the aerodynamic drag, rolling resistance and mass is taken into account by programming tractive resistances into the control unit of the chassis dynamometer.
Challenges related to measuring the fuel consumption, alternative ways for measuring it and elements affecting the results and accuracy have been dealt with in more detail in the annual report of 2003.

Simulating real driving conditions on a chassis dynamometer requires accurate given values for the tractive resistances. In order to determine the tractive resistances for different types of vehicles, several on-the-road coast-down tests were made as part of this sub-project. In the coast-down tests of summer 2003, the vehicles were accelerated up to a speed of 90 km/h and then got to roll until a complete stop. The tests were made with both fully loaded and empty vehicles. Every measurement was completed at least three times in both directions of the road, which adds up to at least six measurements per vehicle/weight-combination. This way a tractive resistance data base was formed, by which it was possible to define the tractive resistances for the most common heavy-duty vehicles. Figure 6 shows power needed to overcome tractive resistances for different vehicles in terms of speed (power needed on the driving wheels, acquired through the rolling tests). How to determine the tractive resistances is described in more detail in the annual report of 2004.

![Driving resistances against speed for different vehicle categories (fully loaded)](image)

*Figure 6. Power needed to overcome tractive resistances for fully loaded vehicles in terms of speed.*

The tractive power for vans, when driving at a speed of 90 km/h is some 20 kW. While driving at the same speed with a 60 ton full-trailer vehicle combination the power is roughly 180 kW. By lowering the speed of a heavy-duty vehicle from 90 km/h to 80 km/h, the tractive power declines and the fuel economy improves by some 20%. The tractive power for a bus at a speed of 90 km/h is around 70kW.
Driving profiles

In order to simulate an actual driving situation, not only accurate tractive resistances, but also driving profiles matching real life driving situations are needed. For this purpose typical driving profiles, in other words driving cycles, were created at VTT for urban buses, express buses and trucks.

For urban buses, VTT RTE developed a “Helsinki cycle” which simulates bus traffic in Helsinki. It was based upon data collected earlier. The aggregate Helsinki cycle is made up to two thirds by typical downtown driving, in other words short distances between bus stops, where the average speed is rather low. The remaining one third of the cycle is suburban driving, which is driven on greater speeds. The driving profiles of buses were researched in more detail in one of the sub-projects. Figure 7 shows the velocity profile of the Helsinki cycle. The cycle was also split into two. Helsinki 2 simulates downtown driving and Helsinki 3 suburban driving.

![Helsinki Cycle 1](image)

**Figure 7.** Speed profile for the Helsinki Cycle 1 depicting driving in the Helsinki area.

Specific driving cycles for trucks were determined in cooperation with Transpoint Oy (a major trucking company). These driving cycles simulate typical driving conditions on freeways and highways, and also distribution driving. All cycles were recorded under actual driving circumstances:

- freeway: Lahti freeway, 30 km north from the north junction of Järvenpää
- highway: Route 4, a 15 km road section in both directions between Leivonmäki and Tainio
- delivery services: delivery driving in the metropolitan area
When driving heavy-duty vehicles on freeways, a change in road declivity brings about changes in the workload of the engine even if the driving speed remains nearly constant. Therefore truck cycles include gradients for taking into account the declivity of roads. Even small variations in altitude make the power of a heavy articulated truck’s engine jump between zero and maximum. Figure 8 shows the load profile for the freeway cycle. From the Figure it can clearly be seen how the declivity affects the engine’s workload. The freeway cycle is driven using a cruise controller, which keeps the speed rather constant.

Figure 8. Load profile for the truck freeway cycle.

Besides the driving cycles which are intended for trucks, similar freeway- and highway driving cycles for long distance buses were developed using equivalent methods. The driving profiles were recorded from a Pohjolan Liikenne (a major bus company) coach operating on the Helsinki-Turku-Helsinki route. In connection with recording the driving profiles, the effect of the driving style on fuel economy was analysed. More about this can be found in the annual report of 2004. The developed driving cycles were also put into use in the subproject on tyre research.

The tractive forces are controlled electrically on the chassis dynamometer at VTT. The mass of a vehicle can be simulated within the range of 2.500 – 60.000 kg. Practically this means that the effect of the load on emissions and fuel consumption can easily be analysed by changing the parameters on the dynamometer. In on-the-road measurements the actual load of the vehicle has to be changed in order to make the same analysis.

In the year 2003 an upgrade in the dynamometer’s software was made. The upgrade raised the largest weight to be simulated from 30 to 60 tonnes. Nowadays vehicle combinations of up to 60 tonnes, which is the largest allowed weight, can be simulated.
Factors of errors

Many factors affect the results when measuring a complete vehicle on a chassis dynamometer. Often small differences in fuel consumption between different vehicles (individual vehicles or models) and the influence of different variables on fuel consumption (lubricants, tyres, transmission settings) are to be measured. In order to get the correct results, it is important to take into account all factors. The most important factors to be standardised are the tyres, the engine’s radiator fan, the fuel, the static axle load and the vehicle’s compressed air system. Depending on the driving profile and the features of the vehicle, normally the repeatability of the results between different tests is some 1 – 3%.

Other results of the sub-project

In the task for development of test methods, although not being linked to chassis dynamometer measurements, a measuring arrangement for defining the tractive resistance of a trailer was made. This was made by mounting a load gauge on the coupling of the truck. The system is to its concept a hydraulic system. It has got two pressure sensors, with different effective ranges, for measuring the pull and respectively two pressure sensors for measuring the thrust. In addition to the above-mentioned, the system also includes electromagnetic valves for protecting the most sensitive pressure sensors (Figure 9). The arrangement for measuring the pull was put into practice in, among others, the summer of 2004. In cooperation with Transpoint Oy, measurements of 4- and 5 axle trailers were made. More information on these measurements can be found in the annual report of 2004.

Figure 9. The instrumented coupling for measuring a trailer’s tractive resistance.
3.2 FACTORS AFFECTING FUEL CONSUMPTION AND CONSUMPTION OF DIFFERENT TYPES OF VEHICLES

General

In this sub-project, fuel consumption for different types of vehicles was defined as a function of the load in various types of driving. The behaviour of a fully loaded and an empty vehicle can easily be simulated on the chassis dynamometer. Performing the tests on a chassis dynamometer makes the measurements a whole lot easier, compared with on-road measurements. Weather conditions and additional traffic on the roads are sources for error in on-road measurements.

Several factors affect the actual fuel consumption of a vehicle in a certain driving task. The driving profile, as well as the weight category of the vehicle, has an influence on fuel consumption. The driving profile stands in this case for a velocity graph or possibly the combination of a velocity graph and a road gradient profile. The emergence of fuel consumption can be divided into two principal factors. Firstly, how efficiently the energy held in the fuel can be transformed into mechanical work in order to move the vehicle. Secondly, how much energy in the first place is needed in order to move the vehicle (compare Figure 1).

The energy efficiency for the whole power-train of a vehicle, on a certain driving profile, can be measured on a chassis dynamometer. By putting into proportion the amount of used fuel to the work made on the driving wheels, the energy efficiency for the entire power-train is received in g/kWh. That is to say that the result directly tells how efficiently the vehicle can produce the needed work on the driving wheels. The format is the same as for the engine. In this research the results have although mostly been reported as the consumed amount of fuel per driving distance (l/100 km), since this is the figure that is most commonly used for vehicles in Europe.

The mechanical energy produced is used for overcoming tractive resistances, differences in altitude and for accelerating the vehicle. The last two are directly dependent on the vehicle’s mass and changes in velocity and altitude. The tractive resistances for their part, are formed by the rolling- and air resistance.

In case the vehicle does not have to be slowed down by braking (including engine brake), the workload done for overcoming changes in velocity and altitude will be regained in the next downward slope, or when the speed is stabilised. Therefore it is all about accumulation of energy, not losses in energy. Consequently the fuel efficiency is influenced only by the efficiency of the power-train on the load profile in question and the air- and rolling resistance forces. This is also always the case when driving at constant speed on flat land.

For most heavy-duty vehicles the rolling resistance is dominant when driving at speeds of 60 – 90 km/h. When the speed increases to over 90 km/h, the air resistance becomes greater than the rolling resistance (see Figure 1). Both tractive resistances are therefore of
importance when driving at highways. Even the slightest changes in them can clearly be seen in the fuel economy of a vehicle.

In dynamic driving, the fuel economy although mostly depends on the mass of the vehicle. Figure 10 shows the dependence of mass on fuel economy when driving a heavy-duty vehicle in the highway cycle. The illustration clearly shows how a semi-trailer truck moves easier than a full-trailer combination truck. This is due to the fact that both the air resistance and rolling resistance are smaller for the semi-trailer truck. Aerodynamically a full-trailer combination truck has got two points of discontinuity; one between the driver’s cabin and the cargo space and one between the cargo space and the trailer. A semi-trailer truck has got only one point of discontinuity, the one between the driver’s cabin and the cargo space. Vehicle mass also affects rolling resistance.

![Graph showing fuel consumption in the highway cycle](image)

**Figure 10.** The fuel consumption of vehicle combinations in the highway cycle in terms of vehicle mass.

Figure 11 presents as an example the effect of different types of trailers (4- and 5 axle) and air deflectors on the tractive resistances. More information on these measurements can be found in the annual report of 2004. By changing the type of trailer (from a 4- to 5 axle) and by adding an air deflector to the truck tractor, the fuel economy of a full-trailer vehicle driving at a speed of 80 km/h will improve by some 10%.

Even for buses, the vehicle’s mass and air resistance affect the tractive resistances (Figure 12). In highway measurements, made in the summer of 2003, the tractive resistances for two coaches, with different structures, were compared against each other.
The coaches were Carrus – Scania K 113, which represents a traditional steel frame design from the late 1990’s, and Kabus TC 6Z3, which represents a new all-aluminium light-weight structure design. The Kabus has also got an aerodynamically favourable shape.

Figure 11. The air deflector’s –and different trailer type’s effect on tractive resistances.

Figure 12. The tractive resistances of a conventional and a light-weight coach.
Fully operational the Kabus weighed only 9,900 kg, while the Carrus bus weighed 13,900 kg. In addition to the difference in weight, the Kabus bus also proved to be a better working concept aerodynamically; this can clearly be seen from the graphs showing the tractive resistance (Figure 12). When driving at a speed of 80 km/h the power requirement of the light-weight bus was about 25% lower than that of the conventional bus. The tractive resistances for half load have been calculated for the masses 12,500 kg and 15,800 kg. The resistances shown in the graph are power needed at the driving wheels.

A lower power requirement also prepares for the use of a smaller engine, which again improves the fuel economy even more than the decrease in tractive resistances. The engine displacement of the engine in the conventional coach is 11 litres, whereas the engine displacement of the Kabus is only 5.9 litres.

**Truck comparisons**

The specific fuel consumption for no less than 16 new Euro 3-class trucks were measured on the chassis dynamometer during the years 2004 – 2005. The vehicles represented four different weight categories, 18 ton, 26 ton, 42 ton and 60 ton. Depending on the weight category, measurements were made for three or four load levels. The highway-, freeway- and delivery service driving cycles developed in cooperation with Transpoint Oy were used. In addition to fuel economy, the emissions of the vehicles were also measured.

It was agreed that no brand names were to be disclosed in the truck comparison. The decision was made mainly because the trucks were on loan from various sources. Therefore the representativeness of the vehicles could not be 100% guaranteed. As a result the different vehicle brands were encoded by letters (A, B, C and so on). In future research stages it is planned to announce the fuel consumption of different brands.

Differences in fuel economy were substantial, at most up to 15% (42 ton combinations, no load). Figure 13 shows an example of the fuel economy for 60 ton full-trailer combinations. Differences in fuel economy in this group were at their biggest with fully loaded trailers. Some of the difference can be explained by turbo-compounding, which turns waste energy from the exhaust gases into mechanical work. The two least consuming 60 ton trucks had turbo-compound engines. In order to determine the impact of turbo-compounding, a comparable model of brand B not equipped with turbo-compound was measured. The result was a 3 – 3.5% higher fuel consumption on maximum load. The fuel consumption with an empty trailer was about 1% higher.

In exhaust emissions the dispersion was even greater. The particle emissions of a high-emitting 42 ton semi-trailer truck, for instance, can be up to 4 times bigger than those of a clean-running truck. When it comes to NO\textsubscript{x} emissions, emissions varied by a factor more than two (Figure 14).
Figure 13. The fuel consumption of 60 ton vehicle combinations for the highway and freeway cycle (vehicles measured in 2004).

Figure 14. NOx and PM emissions (relative to work at the driving wheels) of 42 and 60 ton combinations for the highway cycle (vehicles measured in 2004). Vehicles measured without load, half loaded and fully loaded.
During the final year of the project, in year 2005, some interesting comparisons could be made when the first two Euro 4 trucks came in for measuring. Similar Euro 3 versions of these trucks (brand A and C) had been measured in 2004. The Euro 4 model of brand A (AE4/42) differed from the Euro 3 version by not only having exhaust gas recirculation (EGR), but also an oxidation catalyst and turbo-compound. The Euro 4 version consumed, in average, about 1.4% less in highway- and freeway cycles than the comparable Euro 3 version (Figure 15). This is mainly explained by the use of turbo-compounding.

The other Euro 4 truck (CE4/42) also had an EGR-system installed, but on top of that it also had a particle catalyst (so called partial-PDF) mounted to it. The change from Euro 3 to Euro 4 standards could for this brand be seen as an average increase of 2.7% in fuel consumption in highway- and freeway cycles (Figure 15). The emissions, on the other hand, were low – which can be expected from Euro 4 trucks. Despite all this, the Euro 4 truck of brand C had a better fuel economy than the Euro 4 truck of brand A.

Figure 16 shows measured NOx- and PM values for the Euro 4 trucks in the highway and the freeway cycle. The average results for all the Euro 3 trucks that have been measured so far have been included in the illustration as a reference. The unit in the figure is in grams of emission per work on the driving wheels (g/kWh). Therefore the results cannot be directly compared to those of the engine tests, where the results are in proportion to work on the engine crankshaft.

By using 1.5 as a coefficient, for taking into account losses caused by the power-train and auxiliary devices, certain conclusions can be made. The limit values for Euro 4 class engines in the ETC – engine test are 3.5 g NOx and 0.03 g PM/kWh. If the coefficient 1.5 is used on these values, the reference values for the chassis dynamometer test-stand would be about 5 g NOx and 0.05 g PM/kWh.

The results for the Euro 4 truck (brand A) are shown in Figure 16 as triangular points on a yellow background. The results were somewhat as expected when it comes to emissions of NOx. For both the highway- and freeway cycles, the lowest level of load caused the highest emissions of NOx. What comes to particle emissions, the levels were typically equal to those of the Euro 3 trucks in average. The dispersion between different load levels was although great (0.04 – 0.13 g/kWh). The lowest particle result was close to the proportioned limit value and the biggest about triple.

The results for the Euro 4 truck of brand C can be seen in Figure 16 on a green background. The results for this truck corresponded to the results that were expected, also concerning particle emissions. The emissions were, depending on the load, 0.02 – 0.03 g/kWh. This is about a fourth of the values of Euro 3 trucks in average (the official Euro limit value for particles decrease to a fifth, from 0.16 g/kWh to 0.03 g/kWh in the ETC – test). The NOx emissions for the Euro 4 truck of brand C were equivalent to those of the Euro 4 truck of brand A.
Figure 15. Fuel consumption of 42 ton Euro 4 trucks (AE/42 and CE/42) for the highway and freeway cycle. The striped columns represent Euro 3 vehicles measured in 2004.

Figure 16. NOx and particle emissions of 42 ton Euro 4 trucks (AE/42 and CE/42) for the highway and freeway cycle. Vehicles measured without load, half loaded and fully loaded.
Effect of driving style on fuel consumption

During the defining of driving cycles for coaches in early 2004, the impact of speed limiters and cruise controllers on fuel economy was studied. The research was made on one of Pohjolan Liikenne’s coaches operating the Helsinki – Turku – Helsinki route. A Scania K 114 IB-B bus from 2003 was selected for the tests and equipped with a CAN-data bus reader, a GPS receiver and an air pressure gauge.

The route was measured for three days and the driver was asked to drive in a chosen way. A driving style where the driver set the speed of the vehicle by using the throttle pedal was used as the reference level. The task was to keep the speed as close to the speed limiter’s set value as possible, though without activating the speed limiter by accident. In one mode the bus was operated using the cruise control. In this case the cruise control was used as much as possible and set close to the speed limiters value, again without activating the speed limiter by accident. In the last mode, the speed limiter was let to control the speed always when the traffic situation allowed it. Due to speed limits, the speed limiter was used only on freeways where the never-exceed speed was 100 km/h.

The recorded profiles were repeated on the chassis dynamometer. This way the measurements could be made without circumstantial factors affecting the results. Figure 17 shows the fuel consumption for the different driving modes, on both highway and freeway. In freeway driving, the difference in fuel consumption was within the accuracy the measurement when the speed was controlled by the driver or the cruise control. When driving against the speed limiter, the fuel consumption increased by some 3% compared to “normal” driving. Differences of some 2% were recorded when driving on a highway, but there were also differences in driving speed.

Taking into account the realised speeds and changes in the need of power due to the changes, it could be shown that the use of the cruise control increases fuel consumption by roughly 1% and driving against the speed limiter by some 2%. Some of the differences in fuel economy can also be explained by variations in the engine speed, something which affects efficiency. Hereby it can be concluded, that the fuel efficiency of a modern heavy-duty vehicle does not necessarily suffer from the use of a cruise control or from driving against a speed limiter. The fuel efficiency can instead be remarkably improved by lowering the driving speed and by foreseeing incoming events. The engine in question had an electronic governor. The results could have been completely different in case the tests would have been made on an older type of engine with a mechanical governor.

For urban buses, the effect of different transmission settings on fuel economy was researched. The measurements were made on a Euro 3-standard bus. The tests were carried out by using the Helsinki driving cycles. The combination cycle, Helsinki 1, was driven using default settings. The suburban cycle, Helsinki 3, was driven using default- eco settings. The metropolitan driving cycle, Helsinki 2, was driven using default- eco- and “sport” settings. In the Helsinki 2 cycle, the difference in fuel economy between the most efficient (eco) and most uneconomical (“sport”) was about 5% (Figure 18).
Fuel consumption of Scania K114 IB-B long distance bus with different driving methods.

- Driver controls the speed: 97.7 km/h
- Cruise control: 97.4 km/h
- Speed limiter: 99.7 km/h
- Nominal fuel consumption: 81.8 km/h

Figure 17. The effect of driving style on fuel consumption.

Nominal consumption at driving wheel with different transmission settings
Scania Euro 3 citybus in Helsinki cycles

- Helsinki 1 (combination): -1.70%
- Helsinki 2 (urban): 2.80%
- Helsinki 3 (suburban): -0.9%

Figure 18. The effect of transmission settings on fuel consumption.
Engine- and transmission measurements

Differences in fuel economy between two parallel engine versions were tested in an engine test bench. In combination with one of the engines, two different transmissions, manual and automatic, were also measured. All the components were such that are used by Kabus Oy in their bus production. The objective for the tests was to clarify which engine type gives the best fuel economy and to what extent the type of transmission affects the fuel economy.

The tested engines were Cummins ISBe 275-30 and 220-30. The numbers 275 and 220 stand for the maximum output of the engines in horsepower. The engine displacement of the engines is 5.9 litres.

The engines were installed in a transient type engine test-stand at VTT, by which measurements according to the Directives 1999/96/EC and 2005/55/EC could be made. Unlike what is stated in the Directive, the engines were mounted including their auxiliary devices (the air compressor and generator were connected). Therefore the results cannot be directly compared to the limit values of the Directives. The fuel used during the tests was a commercial low-sulphur fuel. Data for the engines is shown in Table 1.

<table>
<thead>
<tr>
<th>Engine</th>
<th>Cummins ISBe275 30</th>
<th>Cummins ISBe220 30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design</td>
<td>6-cylinders in-line, turbocharged air to air intercooler</td>
<td></td>
</tr>
<tr>
<td>Cylinder displacement</td>
<td>5.9 l</td>
<td></td>
</tr>
<tr>
<td>Max. torque</td>
<td>950 Nm / 1500 rpm</td>
<td>820 Nm / 1500 rpm</td>
</tr>
<tr>
<td>Max. output</td>
<td>202 kW (275 hp) / 2500 rpm</td>
<td>162 kW (220 hp) / 2500 rpm</td>
</tr>
<tr>
<td>Fuel system</td>
<td>Common rail, Bosch HPCR</td>
<td></td>
</tr>
<tr>
<td>Emission level</td>
<td>Euro III</td>
<td></td>
</tr>
</tbody>
</table>

Engine maps were measured for both fuel economy and exhaust emissions. The emission levels of the engines were also measured using the ESC and ETC –certification cycles and the Braunschweig bus cycle transferred to the engine test bench. The actual certification requirement for a Euro 3 type engine is the ESC –test (and ELR smoke test).

The Braunschweig cycle was first completed running a bus on the chassis dynamometer. A comparable load profile was then collected from the CAN –data bus. This load profile was afterward repeated in the engine test bench. A bus weighing 9, 11 and 13 tonnes was simulated in the Braunschweig cycle. Even the smaller engine was able to follow the Braunschweig cycle when simulating the 13 ton weight.

Both the manual- and automatic transmission tests were made on a Cummins ISBe 275 30 engine. The performance of the transmissions was studied in both steady-state load points and dynamic cycles.

The engine map measurements were made with a matrix of 40 measurement points. Emission of particulate matter was recorded in 21 points. In addition, the torque needed for rotating the engine was measured for eight different speeds of rotation. This amount of
torque is equal to the braking torque of the engine. Apart from the points of full load, the
measuring matrixes for both engines consisted of the same measuring points. The “iso-
curves”, describing fuel consumption, that were formed as a result of the engine map
measurements are shown in Figure 19.

The characteristics for both engines are similar. The fuel consumption is at its lowest when
running at low revolutions with moderate torque. This area, where the specific
consumption is less than 210 g/kWh, is shown in Figure 19 as the lightest shade of green.

The lowest measured fuel consumption was 208 g/kWh for the 275 hp version (1250
rpm/686 Nm) and 210 g/kWh for the 220 hp version (1250 rpm/549 Nm). The 220 hp
version consumed less than the 275 hp version in every shared load point, except for one
point. For the measured points (except for idling) the proportional difference was in
average 4.2% in favour of the less powerful engine. Figure 19 shows that the specific
consumption for the 220 hp version is lower than that of the 275 hp version between 1400 –
2400 rpm over almost the whole area of torque.

In the ESC- and ETC –tests the engines performed as expected. They both reached the
Euro 3 emission level. The results from the Braunschweig test is shown in Table 2.

<table>
<thead>
<tr>
<th>Engine</th>
<th>Simulated weight</th>
<th>CO g/kWh</th>
<th>PM g/kWh</th>
<th>THC g/kWh</th>
<th>NOx g/kWh</th>
<th>Fuel kg/test</th>
<th>Fuel g/kWh</th>
<th>Work kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>220 hp</td>
<td>9 t</td>
<td>3.17</td>
<td>0.107</td>
<td>0.14</td>
<td>6.53</td>
<td>2.75</td>
<td>258</td>
<td>10.7</td>
</tr>
<tr>
<td>275 hp</td>
<td>9 t</td>
<td>5.04</td>
<td>0.277</td>
<td>0.16</td>
<td>7.49</td>
<td>2.90</td>
<td>277</td>
<td>10.4</td>
</tr>
<tr>
<td>220 hp</td>
<td>11 t</td>
<td>3.32</td>
<td>0.108</td>
<td>0.11</td>
<td>6.15</td>
<td>3.07</td>
<td>259</td>
<td>11.9</td>
</tr>
<tr>
<td>275 hp</td>
<td>11 t</td>
<td>6.40</td>
<td>0.274</td>
<td>0.02</td>
<td>6.59</td>
<td>3.26</td>
<td>276</td>
<td>11.8</td>
</tr>
<tr>
<td>220 hp</td>
<td>13 t</td>
<td>3.04</td>
<td>0.104</td>
<td>0.06</td>
<td>6.01</td>
<td>3.10</td>
<td>252</td>
<td>12.3</td>
</tr>
<tr>
<td>275 hp</td>
<td>13 t</td>
<td>4.75</td>
<td>0.280</td>
<td>0.03</td>
<td>6.55</td>
<td>3.35</td>
<td>273</td>
<td>12.2</td>
</tr>
</tbody>
</table>

It could be seen from both the ETC- and Braunschweig cycles that the less powerful
engine is 6 – 10% more fuel efficient when using the same load (calculated on the base of
the specific consumption).

Technical specification for the tested gearboxes can be found in Table 3. The gearboxes
were mounted as an extension to the Cummins ISBe 275 engine.

<table>
<thead>
<tr>
<th>Table 3. Technical specification for the tested transmissions.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manual transmission</td>
</tr>
<tr>
<td>Automatic transmission</td>
</tr>
</tbody>
</table>
Three different rotational speeds (1250, 1750 and 2250 rpm) and three different levels of load were measured steady-state. In addition, measurements were made for the manual transmission on 2650 rpm and a 40% load. The measuring points were taken from the matrix of the engine map measurements. The fifth and sixth gears were used when measuring the manual transmission and the fourth, fifth and sixth when measuring the automatic transmission.
When running in fifth or sixth gear, the manual transmission added in average only 2 – 3% to fuel consumption, compared with the engine without transmission. Hence the manual transmission is fairly energy efficient. No remarkable difference was found between the indirect (5.) and direct (6.) gear. In absolute values the manual transmission only adds 0.06 – 0.6 l/h in fuel consumption.

Figure 20 shows the fuel consumption penalty of the automatic transmission. The range of fluctuation is rather big, 4 – 50%. The losses are at their biggest when running at high rpm and light load. At its best, the efficiency of the automatic transmission is almost as good as that of the manual transmission, but at low load the efficiency is poor. The fourth gear was the most efficient, the sixth gear the least efficient of the measured gears. In absolute values the automatic transmission adds 1.2 – 3.5 l/h in fuel consumption compared with the engine alone.

![Figure 20. Additional fuel consumption caused by the automatic transmission.](image)

### 3.3 MODELLING THE FUEL CONSUMPTION OF VEHICLES/MODELLING THE DRIVER

#### General

The idea of modelling is to make it possible to calculatorily estimate the fuel consumption for different types of vehicles. It is rather impossible to experimentally evaluate the effect of different transmissions or final drives on a given route. When the model is “calibrated” well enough, it can be used for defining the specifications for a vehicle or for optimising the selection of vehicles. For simulating fuel consumption, the commercial ADVISOR modelling program was used. Two buses were modelled using this program. In addition, the models were utilised for simulating different driving styles and in the development work of the driver’s aid.
The ADVISOR software proved to be a powerful tool for simulating fuel consumption. The uncomplicated flexibility of the software’s simulation models is helpful in a variety of simulations. The ADVISOR software can, for instance, help choosing the right components for a vehicle in order to make it as fuel efficient as possible on a certain route.

**Modelling of a vehicle**

The Laboratory of Automotive Engineering at Helsinki University of Technology (HUT) modelled two different buses; a three-axle Volvo B10B LE urban bus and a Kabus TC-6Z3/7300 coach equipped with a manual transmission. An engine map for specific fuel consumption, generated at VTT, was available for both vehicles. In the case of the Kabus coach, the engine map was generated based on data from the CAN-data bus. The simulated results were compared against results measured on the chassis dynamometer. The well-known Braunschweig cycle for urban buses and the Helsinki-, highway- and freeway cycles developed for the project were used.

The vehicles were modelled using measured data or based on ready models of the ADVISOR software. Modelling of the Volvo bus carried off rather well. The simulated fuel consumption of the Volvo was 95 – 113% of the measured values. The modelling was more accurate in urban traffic than in regional traffic where the biggest differences occurred.

The point of application of electrical and other auxiliary loads on fuel consumption was also simulated. Based on results of the simulation, it could be concluded that in practice only the average auxiliary load has an effect on fuel consumption, not timing of the load. In addition, simulations with different parameters were made in order to study how much the parameters actually affect the results. Due to the structure of ADVISOR, even bigger entities in the model, such as the engine and transmission, can rapidly be changed. Table 4 includes a few examples of how different parameters affect the fuel consumption (Braunschweig cycle).

<table>
<thead>
<tr>
<th>Modification</th>
<th>consumption [l/100km]</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>60,7</td>
<td>100</td>
</tr>
<tr>
<td>(C_d) value 0,5 (\rightarrow) 0,79</td>
<td>61,4</td>
<td>101</td>
</tr>
<tr>
<td>Different tyres (Tyres of Kabus =&gt; Volvo)</td>
<td>57,5</td>
<td>95</td>
</tr>
<tr>
<td>Consumption of mechanical auxiliary devices 5kW (\rightarrow) 10kW</td>
<td>64,8</td>
<td>107</td>
</tr>
<tr>
<td>Consumption of electrical auxiliary devices 2,5kW (\rightarrow) 5kW</td>
<td>62,6</td>
<td>103</td>
</tr>
<tr>
<td>Consumption of electrical auxiliary devices 2,5kW (\rightarrow) 10kW</td>
<td>66,4</td>
<td>109</td>
</tr>
<tr>
<td>Final drive 4,87 (\rightarrow) 4,00</td>
<td>74,4</td>
<td>123</td>
</tr>
</tbody>
</table>
Modelling gear shifting and the driver

In this part of the project, models for shifting gears were developed and the effect of different gear shifting strategies on fuel consumption was analysed. The first case was to model and simulate the gear shifting of a heavy-duty vehicle equipped with a manual transmission. This had proved to be a rather demanding task. In addition to the Kabus bus, new simulation models were the truck tractor of a trailer combination and a delivery vehicle. The two new models for heavy-duty vehicles were created in the same way as the previously developed bus models. Reliable data over components, for modelling the vehicles, was received from the manufacturers. The engine map was produced based on measurements made on the chassis dynamometer at VTT.

The modelling of heavy-duty vehicles, equipped with manual transmissions, was made in order to develop a model simulating gear shifting behaviour for ADVISOR. At the same time it was estimated whether a simulator-software could be used to control the gear shifting behaviour of an actual driver. The impact of gear shifting on fuel economy was also researched. This was done by simulating three different types of heavy-duty vehicles, equipped with manual transmissions, using six different gear shifting strategies.

A program segment for controlling gear shifting strategy was added to the transmission part of the actual simulation model. This program segment shifted gears based on a pre-defined logic and thereby produced different driving behaviours. The logics were based on taking into account the driving environment and the performance of the vehicle in gear shifting. The impact of the surrounding traffic was not taken into account. Three typical delivery cycles, recorded in advance, were used. The cycles also included the height profile for the road, which was one parameter to affect the gear shifting.

The simulations proved that the way the driver shifts gears has got some influence on fuel economy, and that it is closely bound to the driving situation. The ADVISOR model for a heavy-duty vehicle equipped with a manual transmission can be enhanced by adding a feature simulating the gear shifting behaviour of an actual driver. Even though generating the basic model was rather easy, emulating the actual behaviour of a driver required a lot of testing and development.

The effects on fuel consumption caused by different gear shifting strategies can be seen in Figure 21 (simulated results). The blue colour represents the truck tractor of a trailer combination, the green colour a long distance bus and the red colour a delivery truck. The difference in fuel consumption between the different gear shifting strategies is at most some 5%.

Optimising the driving cycle and development of the driver’s aid

Driving cycles for two urban bus lines were analysed and used in the development work of the driver’s aid. More information about the driver’s aid can be found in section 3.4. The analysis of the driving cycle consisted of an analysis of the actual measured data and the creation of an optimal driving cycle for two urban bus lines.
Figure 21. Fuel consumption for different gear shifting strategies (A – F). Blue= truck tractor, green= coach, red= delivery vehicle.

To investigate the effects on fuel consumption of how a bus is driven, two bus routes were analysed in detail. Actual driving patterns for bus lines 550 (the so-called Joker-line) and 58 were recorded. A small theoretical study on factors affecting fuel consumption in stop-and-go driving according to a fixed time schedule was carried out. In practice best fuel economy is achieved when accelerating economically, avoiding accelerating-braking-accelerating patterns and speeding, and setting target speeds for every stop spacing.

Optimal driving cycles were created out of the recorded ones for the purpose of simulation. The optimal cycle was based on the findings listed above, targeting driving as economically between the bus-stops as possible. Figure 22 clearly shows the idea of optimising the driving cycle. The analysis of line 550 was also groundwork for the development of the driver’s aid device.

Three different ”optimal” driving cycles were created on the base of the measurements of lines 550 and 58. The difference between them was the level of acceleration. “Optimal 100%” equals an almost full acceleration, while “Optimal 50%” equals a two times slower acceleration than the above mentioned. The results of the simulation regarding fuel savings are shown in Figure 23. The results of the optimal cycles have been compared against the simulated results of the recorded cycles. Thereby the differences between the measured and optimal driving cycles, concerning fuel economy, can clearly be seen.

It is economically advisable to accelerate rapidly. Figure 23 shows that the savings potential when accelerating quickly is between 10 – 18%. The savings potential for driving guidance is greater for the lengthy Joker-line than for line 58 which consists mostly of urban driving.
The logic control of the driver’s aid was developed by applying results from the simulations. The basis for the programming of the driver’s aid was the optimal driving cycle for the driving route, which had evolved from the analyses of the driving cycle. Data concerning the driving cycle of the bus line, timetables, stop listings and geographical information on the bus stops were needed for the simulations. The above mentioned data was collected by measurements done in the bus. A separate simulation environment was created in the MATLAB software to make it easier to develop the software of the driver’s aid (Figure 24).

In order to make the guidance system work, the software had to be able to determine the location of the bus in relation to the bus stops. The location of the bus in relation to the next stop was calculated by using an algorithm developed for the purpose. The algorithm
calculates, by using position data, where exactly on the line the bus is moving in relation to the bus stops. This makes it possible to give real time driving instructions to the driver. Every time the bus has passed a bus stop, the software calculates the difference in the actual time with the pre-defined timetable. This way the software can increase or decrease the optimal driving speeds for the remaining bus stops intervals in order to keep the bus running on time.

The following information was determined for the simulation:

- Position data for the bus line and the bus stops
- Speed limits and timetables for the bus line
- Distance between bus stops
- Target speeds between bus stops
- Driving cycle

Figure 24. Programming the driver’s aid using MATLAB.
3.4 DEVELOPMENT OF A DRIVER’S AID DEVICE FOR BUSES

General

An active real-time driver’s aid device, for guiding the driver to a more fuel efficient driving style, was developed in this sub-project. Especially for buses, both the quality of service and running on time has to be taken into account. The actual development work was carried out as a co-operation between Helsinki University of Technology and VTT.

Features of commercial information systems were analysed in the first stage of the task. User profiles were recorded by installing data collectors on different types of vehicles. Ways to exploit the CAN- data bus for collecting data and ways to implement it into the driving guidance system were researched.

Mapping of the market situation was subcontracted to Helsinki Polytechnic Stadia. Several different information systems for monitoring fuel consumption and the driving style are available on the market. Some of these information systems give feedback to the driver on his/her driving style. They can also give, for instance, guidance when to shift gears. There are although no information systems available that combine the position- and timetable data of a line with vehicle data into information for guiding the driver.

Theory

In ordinary bus traffic in Helsinki, up to three quarters of all the energy used for moving the bus is lost into heat when braking (Figure 25). Only a fourth is used for overcoming actual tractive resistances (air resistance, rolling resistance). This reflects the particularly great part of the total amount of used energy that is needed for accelerating the bus.

It was decided to concentrate on guidance for urban bus traffic when the first prototype of the driver’s aid was created. Considerable variations in speed and fixed repetitive routes are typical for urban busses. The quality of the provided service, and especially running on time, are important elements in passenger traffic.

The driving event of an urban bus on a stop spacing is split into four different stages for examination; starting, accelerating, constant speed and braking.

Variables/values to be measured during the acceleration phase could for instance be the greatest momentary acceleration or the change in acceleration. This information on the motion state can be used for indexing the driving style. Instant feedback on the acceleration could also be given, if the driver exceeds the pre-defined limiting values for acceleration. This feature was although not included in the first prototype.
Figure 25. Split-up of energy use for the Braunschweig bus cycle.

The greatest part of total work done between two bus stops is done during the acceleration phase. This is emphasised particularly on a short stop spacing (Figure 26). Therefore, accelerating as efficiently as possible is to be pursued.

Figure 26. Energy spent on a bus stop spacing.
The driving event of an urban bus is closely bound to the schedule of the route. Optimising fuel consumption only for the route cannot therefore be done. The optimisation has to be done within the limits of the schedule. The time used for accelerating and braking on a short stop spacing strongly affects the driving speed that is needed for running on time. In order to run on time the top speed has to be increased respectively. Increasing the driving speed again adds to changes in speed, which again gives a worse fuel economy (Figure 26). Due to this and the efficiency of the acceleration, the driver should accelerate rapidly enough, although without the transmission shifting down (without activating the kick-down function).

The leading principle of the driver’s aid device is to guide the driver to accelerate rapidly and to drive at an as low constant speed as possible, within the frames of the schedule. Guidance of the braking event was due to safety reasons still left out at this stage.

The study of the theoretical savings potential, gained by the use of the driver’s aid device, was incorporated into a thesis made at Helsinki University of Technology (Antti Lajunen). Mr. Lajunen simulated the lines 58 and 550 in his thesis using the ADVISOR –software. His conclusion was that 10 – 18% fuel could be saved without the schedules being affected (view section 3.3).

The prototype

The system constantly monitors the vehicle’s state of motion, position and whether it is running on time. The state of motion of the vehicle is obtained from its CAN–data bus, no extra sensors are therefore needed. The GPS–satellite system is utilised for locating the vehicle and the bus stops. The schedules of the lines, speed limits, target speeds, bus stops and coordinates of the bus stops were entered manually into the system at the demonstration stage. For a commercial system, more attention should be laid on automating the programming of different lines in order to minimise the cost of labour.

The driver’s aid device calculates, based on obtained data and the defined schedules of the lines, at which speed the final part of the route should be driven. The driver’s aid adapts to the realised schedule and tries to keep the bus running on time. The device starts to guide the driver already at the beginning of the line; therefore great deviations from the schedule will not occur if the traffic situation is normal. Therefore only a little fine adjustment of the driving speed is needed in order to keep the bus running on time. If the bus is behind schedule, the guidance-speed will be increase, at its most, to the speed limits.

Forwarding the information to the driver was tried to be kept as simple as possible, so that it would not take the driver’s attention of the road. The guidance monitor has got four rows. The uppermost shows acceleration guidance, the second one guidance for driving speed, the third target speed in numbers and the undermost the name of the next bus stop (Figure 27).

In addition to guiding the acceleration when departing from bus stops also occasional accelerations caused by the traffic (for instance traffic lights) were guided. Accelerating too modestly will make the background of the uppermost row turn yellow and a message
tells to accelerate faster. Accelerating too fast again will make the background turn red and a message tells to ease throttle. Deviations from the guidance speed are shown as colour bars located on both sides of an OK –symbol. A green OK –symbol is still shown when the first “fine adjustment” bar lights up (within permitted tolerance).

When driving according to the guidance of the semaphore, both rows equipped with colour codes will remain green. In this case the driver can solely concentrate on the traffic.

![Image](image.png)

**Figure 27.** The screen of the guidance monitor. Kaasu OK= throttle OK, lisää kaasua= increase throttle. (Innopoli & Varha names of bus stops).

The first prototype was built on a laptop as an easily modifiable Labview application. The application did not yet operate completely independently at this stage. It required the user to start the driving-program and the data recording manually. The guidance logic although worked automatically.

**Tests in real driving situations**

In order to test the actual effect of the guidance, a series of test runs were performed on one of Helsinki Bus Company’s Scania Euro 3 urban busses running on line 550 (the Joker line). For defining the reference levels, actual driving profiles were first recorded without the use of driving guidance (normal situation). In order to make the results comparable, the test runs with driving guidance were made using the same driver on the same day of the week and at the same time of the day.

The driver’s aid device worked as expected. The desired acceleration profile and driving speed was passed on to the driver successfully without the observing of the monitor disturbing the actual driving performance. By comparing speed profiles from drives made with and without driving guidance, it can clearly be seen how the driver’s aid managed to cut peaks in speed (Figure 28). The illustration also shows how the guidance speed has been controlled during the drive (light pink line). On the first part of the route the guidance speed was some 4 km/h below the speed limits. From the bus stop of Suursuonlaita all the way to the terminal point at Itäkeskus the guidance speed was set to its maximum value, in other words to the speed limits of the road in question.
Figure 28 also shows the accumulation of work made by the engine, which correlates with fuel consumption. In this example (a skilled driver) the driver’s aid saved some 5% fuel.

The drivers’ comments concerning the driver’s aid device were surprisingly positive. The guidance was considered useful and the way the information was communicated clear. The use of the driver’s aid essentially decreases the need to constantly observe the schedules, since this feature is part of the device’s logic. In case the bus is behind schedule, the driver’s aid increases the guidance speed to, at its most, the speed limits. This suppresses the temptation of speeding in order to run on time. Unintentional speeding will also be eliminated since the driver does not have to watch the speedometer and compare it to the speed limits all the time. The device simply displays a green OK-symbol if the driving speed is adequate.

In one example speeding by 5 km/h was decreased by 82% measured in time of exceeding. Without guidance the speed limits were exceeded by at least 5 km/h for 183 seconds, whereas the speed limits were exceeded by that value for only 33 seconds when the guidance system was in use. Speeding of 10 km/h decreased, in proportion, by 90%. These were mainly “unintended” cases of speeding. The guidance is assumed to have an even greater impact on inexperienced drivers. Measured on the perspective of service quality, driving ahead of the schedule is much worse than being a few minutes late. Driving ahead of the schedule is effectively eliminated by the use of the driving guidance system. In practice, driving ahead of the schedule is made impossible by lowering the guidance speed. In this case the excess time is used for improving the fuel economy, accordingly to the fundamental theory.

![Figure 28. The effects of driver’s guidance on the outcome of the driving of the Joker bus line.](image-url)
3.5 ENERGY EFFICIENCY OF TYRES

General

This sub-project was carried out as a thesis and as separate measurements made at Helsinki University of Technology. The purpose of the thesis was to determine how different types of tyres influence fuel economy. The impact of tyres on safety and operability was also examined. The sub-project was built on a literary research and tests using different types of tyres, both on the road and on the chassis dynamometer at VTT.

Strive for more fuel efficient buses and other heavy-duty vehicles has led to the use of more lightweight components. This has made it possible to increase the payload. One of the tyre industry’s contributions to lightweight components is the wide unit wheel, also called the super-single, which is intended for use on the driving axle. At this moment there are two manufacturers who sell this type of tyres and more alternatives should soon come out on the market. By the use of new super-single tyres, savings in both space and weight are considerable compared to conventional twin wheels. The vehicle will become more than 100 kg lighter and there will be some 30 cm of additional space between the rear wheel arches.

The rolling resistance of tyres has also been considered when designing the super-single tyres. One of the goals of the thesis was to study whether super-single tyres could be used on the rear axles of buses instead of twin wheels.

Measuring rolling resistance and fuel economy

In addition to measuring the rolling resistance (freely rolling tyre on highway or on a chassis dynamometer) a new subject was to indirectly measure the efficiency of the power transmitting tyres by determining the fuel consumption of the vehicle on the chassis dynamometer. The chassis dynamometer at VTT has got rolls of no less than 2.5 meters in diameter. This equipment suits well also for tyre comparisons. Tyres for urban buses were tested using the Braunschweig –cycle. Tyres for coaches were tested using a highway bus cycle created by VTT.

In the rolling tests, made on the chassis dynamometer and using the Braunschweig –cycle, the main comparable products were Michelin’s super-single tyres and congruent twin tires. Other tyres tested on the chassis dynamometer were re-treaded. Variables for the re-treaded tyres were the size of the tyre, degree of wear and the type of the frame. New tyres of the same size from two different manufacturers were compared on the front end axle.

The tests showed that the difference in fuel consumption between the wide super-single tyre and congruent twin tyres is marginal. Dynamometer-driving does not necessarily bring out all the advantages achieved with this new type of tyre. Neither is driving on a steel drum fully equal with driving on an actual road. The tests made on the highway although support the results acquired from the tests on the chassis dynamometer. The difference between the super-single tyre and a twin wheel combination is, at least when driving
straight, not significant. The super-single tyre weighs more than 100 kg less and requires less space, which although is a great advantage. Designing vehicles will be more flexible since the gap between the wheel arches can be made bigger. The super-single tire proved to be more comfortable in the tests made on highways.

The degree of wear was noted to have a big impact on the rolling resistance for re-treaded winter tires. Tyres which had a remaining groove depth of only 33% consumed 4% less fuel than the equivalent new tyre. This is due to a smaller rolling resistance. Re-grooving of a worn out tyre is, based on this result, economically lucrative. Re-grooving can at its best add up to 25% to a tire’s operating life while it is at its most economical stage. Worn out tyres and tyres with only longitudinal grooves do not although offer as good grip as new tyres, which again can be bad for traffic safety. Using re-grooved tyres for heavy-duty vehicles should therefore be timed for the summer when driving conditions are at their best.

Differences in the frame structure of tyres affect the fuel economy, also for re-treaded tyres. A difference in the tyre’s type of frame (different manufacturer) added 1% on fuel consumption compared to similar tyres of the same size and with the same texturing. As with re-grooving, the use of re-treaded tyres can be rationalised by economical reasons. The price for a re-treaded tyre is some 50% less than that of a new tyre. If the customer uses his own tyre frames for the re-treading, the price will drop with an additional 100€ per tyre. One other selection criteria for a coated tyre can be the employing effect for local labour.

The vehicle under which the tyres were tested also affected the results. Based on the rolling tests, a 295/80 R 22.5 tyre has less rolling resistance than a 275/70 R 22.5 tyre. In the fuel consumption measurements, the bigger tyre however consumed roughly 1% more fuel than the smaller one. This was probably due to a change in gear ratio caused by the change in diameter, which in this case worked in the wrong direction. The tested vehicle is intended for 275/70 R 22.5 tyres. The difference between front tyres of different makes was small, only 3.2% in rolling resistance forces.

Tyre pressure is essential for good fuel economy. The rolling resistance of under-inflated tyres is bigger, which worsens the fuel economy. An over-inflated tire on the other hand is not elastic enough for softening the roughness of the road. This puts more strain on the suspension and the bearings than a correct tyre pressure. The life cycle of a falsely inflated tyre is also shorter. Attention should be paid on using the right pressure in tyres. The tyre pressure of the inner tyre in a set of twin wheels should also be checked regularly, even though it might be difficult to reach the valve.

Within this study it was not possible to go deeply into safety issues and requirements for fluent traffic flows. The basic default is that the correct type of tyre is chosen for the purpose of use, also considering safety issues. For Finnish weather conditions, the period of use for bus tyres from fall to fall is reasonable. Especially when many tyres are designed so that they convert from winter tyres to summer tyres as they wear. The safety of a bus can be improved by maintaining the tyres, in other words by observing incipient damages and by regularly checking the tyre pressure. Automatic tyre pressure
monitoring systems will most likely become more common in the future, which makes the maintenance easier and extends the life cycle of the tyres while keeping the fuel economy at an optimal level. As a result of automatic tyre pressure monitoring systems, tyre failures which begin as small leaks can be prevented. This brings down the probability of interruptions caused by tyre failures.

The used measuring method can be considered reliable based on the consistent results of several tests at different times. The tyre with the smallest groove depth always had the best fuel economy.

The results are shown in Figures 29 (urban cycle) and 30 (highway cycle). The significance of the tyres increases along with the speed. The difference between the lowest and the highest value for fuel consumption was some 7% in the urban cycle and some 14% in the highway cycle. The measurements were made on the chassis dynamometer.

![Figure 29. Fuel consumption results (urban bus, Braunschweig cycle). RG= re-grooved, RT= re-treaded.](image)
3.6 THE IMPACT OF THE ROAD SURFACE ON ROLLING RESISTANCE

General

The tyre’s effect on fuel economy was extensively researched in the “Prospects for minimising losses caused by the tyres” part of the project. This gave the inspiration to develop a method for researching how the road surface affects the rolling resistance of tyres, which again affects fuel economy.

The research was divided into three parts; a literary research covering studies of how to measure the rolling resistance on a highway, developing measuring equipment for measurements made on a highway and using the measuring equipment for comparing different road surfaces. The measuring equipment was meant to be placed in NOTRA, a trailer for measuring tyre noise, which had earlier been constructed at HUT. In addition, the suitability of using LONTRA, a trailer for measuring longitudinal traction, for rolling resistance measurements was to be evaluated.

Based on results that could be found from literary works, it can be confirmed that the features of the road surface clearly affect the tyre’s rolling resistance. Different types of road surfaces cause fluctuations of a few percent in a car’s fuel economy. The effect on the fuel economy for heavy-duty vehicles can be even greater. The results from different studies, however, vary quite a lot. Generally it seems like no generalised results and not even a properly working measuring method has been developed, even though the subject has been regularly researched.

Measuring rolling resistances on an ordinary road is a necessary and challenging task. The necessity of it is even emphasised by the wear of the pavement. An experimental road built in a laboratory or a paved roller only describes the features of the pavement when it is still new. The challenges include normal factors connected with measuring technology, such as
driving speed, temperature and so on. An oddity when measuring on a highway is the transverse and longitudinal road inclination, which is a wanted feature for making the water drain away. The road inclination although makes it harder to perform these measurements.

**Measuring equipment and the measurements**

Measuring the rolling resistance using the NOTRA trailer is based on a power sensor which measures the rolling resistance force directly from the axle of the measuring wheel (Figure 31). A special made tyre with the framework of a tyre for a light commercial vehicle and the tread and patterning similar to that of a truck tyre was used as the measuring tyre. Measurements were made on 11 different surfaces and variations between them were noticed. The test strips were selected in company with The Laboratory of Highway Engineering at Helsinki University of Technology. This way the measured road surfaces represented as extensively as possible the different types of actual road surfaces in use. The reliability of the results is although questionable. All sources of error could not be eliminated and neither could the absolute values for the rolling resistance force be determined.

![Figure 31. The instrumentation for the measuring rolling resistance.](image)

The reliability of the measurements could be increased by adding more instrumentation to the device, but the problem is that the basic structure of the NOTRA trailer is not suitable for measuring rolling resistance. Similar problems were run into with the other measuring trailer, LONTRA. The basic structure of the trailer could be functional, but the instruments should be designed for measuring smaller forces and the suspension of the trailer should also be changed.

The biggest credit of the sub-project is the clear and reasonable identification of sources of error. This makes it possible to continue the research in this field in the future. In practice this means constructing a trailer for the sole purpose of measuring rolling resistance. The instrumentation should allow the measurement of both the inclination and the roughness of the road at the measuring tyre. Funding for constructing a purpose built rolling-resistance trailer was applied for.
3.7 FUEL AND LUBRICANT TECHNOLOGY FOR IMPROVED FUEL ECONOMY

General

Modifying fuels and lubricants is a fast and relatively easy way to affect the fuel economy of a vehicle. In the end the traffic contractor makes these decisions himself. The Finnish climatic conditions although constrict the types of fuels that can be used. It is important that the fuel remains liquid also in low temperatures. Friction losses in lubricants can be affected by the composition of the base oil, viscosity and additives in the lubricating oil. In the optimal case the lubricant performs flawlessly in its lubricating task and at the same time minimises friction and exhaust emissions caused by the lubricant itself.

During three years, engine tests were made using two heavy-duty engines (Volvo DH10A and Scania DC11 03). Vehicle tests were made using two trucks. Measurements of transmission oils were made using a test rig which consisted of, among others, an electric motor, a transmission and a final drive gear. The engine tests were made according to the European ESC –test cycle using selected points so that all load levels except for idling were represented. The measurements were made emphasising partial loads. The vehicle tests were made using the VTT freeway cycle, which has been recorded in actual driving on the Helsinki – Lahti freeway.

All engine and vehicle measurements were made using fully warmed-up engines/vehicles. The transmission oil tests were made by simulating a normal start, that is to say that the temperature of the oil was the same as that of the environment. The tested lubricants were partly commercial and partly prototype oils. As good repeatability as possible was strived for in all the experimental arrangements.

Fuel

Depending on the time of the year, there are several diesel fuel qualities with varying cold properties available in Finland. The fuel quality of different seasons also affects fuel economy. Considering fuel economy, it would be best to use summer quality fuel for as long as possible (Figure 32). The volumetric fuel consumption of a bus engine, tested at four points of load at around 1500 rpm, was in average 3.5% smaller when running on summer quality fuel instead of winter quality fuel. The winter quality fuel is pumpable in up to -34 °C. A difference in density explains the results. When the engine is running at a certain power it needs volume-wise more fuel of lower density than it needs fuel of higher density. These differences in fuel economy noticed in the tests are although also caused by other factors (for instance the viscosity and heating value), because differences between the fuels can also be seen when analysing the specific fuel consumption expressed in g/kWh.

The fuel quality also had an effect on the maximum output of the engine. A change in power is mainly explained by the fact that the fuels have different densities. The injection pump can at its most only deliver a certain volume of fuel to the engine, but it is the mass of the injected fuel that is crucial for the amount of produced power. If the same volume of


two fuels of different density is injected into the engine, the fuel with the higher density will produce more power (providing that the heat values in MJ/kg of the fuels do not differ from each other remarkably). A 4.8% higher maximum output was attained using summer quality fuel compared to winter quality fuel of the best cold-features. Engines equipped with electronically controlled fuel injection do not necessarily behave the same way.

The results show that summer quality fuels of as high density as possible should always, if possible, be used in order to achieve the best performance and minimising the volumetric fuel consumption. Some new vehicles equipped with high pressure injection systems have a very powerful fuel recirculation. This means that the temperature of the fuel remains rather high while driving, which lowers the risk of the fuel filter getting clogged. The vehicle operators should therefore thoroughly consult a representative of the vehicle manufacturer for true requirements on cold properties of the fuel.

![Figure 32. Volumetric fuel consumption for different fuels tested in a bus engine. Fuel codes depict cloud point/pumpability limit temperature. Reference is a fuel with a pumpability limit of -34 °C.](image)

**Figure 32.** Volumetric fuel consumption for different fuels tested in a bus engine. Fuel codes depict cloud point/pumpability limit temperature. Reference is a fuel with a pumpability limit of -34 °C.

**Engine oils**

Differences between engine oils were at their most 3% in the engine measurements (Figure 33). A 15W-40 oil was used as reference. The measurements were made using fully warmed-up engines. The differences shown in Figure 33 are the average values of eight measuring points. The differences were largest at small loads, when the relative share of friction losses is big compared to engine net work. Thereby the greatest advantage of fuel saving oils can in the real life be achieved in vehicles that operate at a low average load rate. A delivery vehicle in the urban area could be an example of this.
Figure 33. Changes in fuel consumption for two heavy-duty engines compared to a 15W-40 viscosity class oil. Fully warmed-up engines, 8 steady-state load points.

Differences between engines can be remarkable due to structural differences. The results vary considerably already with two different measured engines. The Volvo engine uses dry sump lubrication, the Scania engine a traditional wet sump. In average, the effect of the oils was, within the measuring accuracy, parallel in both engines. Differences between the oils, however, were more notable in the Scania engine than in the Volvo engine.

Some of the oils used in the engine tests were also tested in vehicles on the chassis dynamometer. The results attained in the vehicle tests were parallel to those obtained in the engine tests. The effect was generally smaller than in the engine tests, which mostly is due to the use of different load rates. The vehicle tests were driven using the freeway cycle in which the average load rate is high. The results obtained from the freeway cycle, using fully warmed-up engines, represent the minimum level of change in fuel consumption between different lubricants (magnitude of 1%).

The viscosity grading is a matter describing the flow properties of the oil on a rather harsh level. Figure 34 shows the correlation between fuel consumption and kinematic viscosity at 100 °C in engine tests. The high-temperature viscosity class is determined at this temperature (for instance SAE –class 40). It can be seen that the correlation between the kinematic viscosity and fuel economy is existent, but not very clear. No single physical variable can be said to have that strong effect, that it would be a dominating factor for the fuel efficiency in a fully warmed-up engine. The chemistry of the lubricant significantly affects fuel economy. The base oil clearly affects the viscosities measured in different ways and different temperatures, but the effect of additives which lower the friction cannot be seen in the viscosity measurements.
Figure 34. Correlation between kinematic viscosity (100 °C) and specific fuel consumption.

Transmission oils

The vehicle tests for transmission oils were made using a Euro 3 truck on the chassis dynamometer. Differences in fuel economy for the transmission oils were under warm conditions within the measuring accuracy (less than 0.5%). This can also be concluded based on Figure 1 (halve losses in power transmission would mean 3% saving in fuel consumption).

Savings can although emerge under cold operating conditions. Stadia performed tests of transmission oils in a test rig installed in a cold room. A 160 kW electric motor was used as the source of power for driving a 16–gear ZF Ecosplit 16S151 manual transmission. The power was transmitted through the final drive to an eddy-current brake.

Tests were made under both cold- and warm settings. At the beginning of the cold cycle the temperature of the oil was -25 °C and in the warm cycle +20 °C. In both cases, friction losses decreased under almost the whole cycle of 25 – 30 minutes, but very slowly in the end. Measured differences in efficiency between the oils were under warm conditions at their most 2 percentage points, more under cold conditions. The influence on the efficiency of the transmission line is not the same as the influence on the entire vehicle’s fuel economy. In other words; a small change in the efficiency of the power transmission will be unnoticeable beside the other power needs of the vehicle.
Summary

A maximum difference of 2 – 3% in fuel consumption was found between the engine oils. This is the average of all load points tested. The differences were even more than 4% in points of partial load. The two engines tested in the engine test stand gave different values for fuel savings, but arranged the oils in the same order of superiority. Vehicle tests were made running fully warmed-up vehicles on the chassis dynamometer on high load and practically constant speed according to the freeway cycle. The tests showed that the engine oil affects fuel consumption by only 1% at its best. Lower average load would probably bring about bigger differences.

The effect of transmission oils on fuel consumption was minimal in the vehicle tests on the chassis dynamometer. Measurements were also made in a special test rig using heavy-duty components. Differences in efficiency between the oils were under warm conditions at their most 2 percentage points. This has no practical significance for the complete vehicle. Differences were greater under cold conditions and the efficiency clearly improved as the oil got warmer.

A realistic fuel saving potential by optimised lubricants (engine and driveline) is 1 – 3%. The saving can be greater under some conditions, e.g., when operating in cold weather conditions.

Availability and functionality greatly affects the selecting of fuel. Using fuel of barely sufficient cold properties is favourable for fuel economy. There is no point in using fuel with unnecessarily good cold features.

3.8 MAINTAINING, UPDATING AND RETROFITTING OF VEHICLES

General

The goal of this sub-project was to clarify to which extent the performance of the actual fleet can be improved by different measures of maintenance and updating. Different commercial techniques claimed to improve fuel economy were also studied. Retrofitting as a way to clean up existing vehicles was also studied. Measurements were made using both the chassis dynamometer and the engine test bench. Two Euro -2 class Volvo DH10A – engines, VTT’s own laboratory engine and a similar engine borrowed from a bus operator were utilised in the engine test bench tests.

“Fuel saving technologies”

The supply and marketing of various auxiliary devices, additives and equivalents aiming at fuel savings is occasionally abundant. Some advertisements guarantee fuel savings of up to several dozen percent. It is worth mentioning that the American Federal Trade Commission has insisted on putting a ban on business operations for certain actors for promising pie in the sky. (United States District Court 2004).

Altogether five commercial “fuel saving technologies” were researched within the project:
- detergents for blending into fuel
- detergents for blending into engine oil
- technology based upon magnetism
- technology based upon an agent for coating metal
- blending air into the fuel

The two first mentioned techniques were studied using a bus on the chassis dynamometer. The other measurements were made in the engine test bench using a Volvo DH10A -engine. None of the tested technologies provided, within the measuring accuracy, measurable fuel savings or an increase in power.

**Reconditioning of an engine**

The tests were made in the engine laboratory at VTT during fall 2004 and late summer of 2005. The object for reconditioning was a Euro 2 –certified Volvo DH10A –engine borrowed from Helsinki Bus Company. The engine had a mileage of more than 700,000 km and had been extracted from a bus due to leaking of liquid.

Table 5 shows measures carried out on the engine. Replacing the thermostat was from the start not part of the plan, but it was changed based on the results of the first tests because the engine was clearly running too cold. The fluid leaks were repaired before launching the tests. Each operation was followed by measurements of engine performance.

**Table 5. The reconditioning programme for the Volvo DH10A bus engine.**

<table>
<thead>
<tr>
<th>Engine to be reconditioned</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Initial measurements</td>
</tr>
<tr>
<td>2 Replacing the thermostat</td>
</tr>
<tr>
<td>3 Changing the oil</td>
</tr>
<tr>
<td>4 Simulating the air filter getting clogged</td>
</tr>
<tr>
<td>5 Adjustment of the valves</td>
</tr>
<tr>
<td>6 Replacing the injector nozzles</td>
</tr>
<tr>
<td>7 Rebuilding of the injection pump</td>
</tr>
<tr>
<td>8 Rebuilding of the turbocharger</td>
</tr>
<tr>
<td>9 Rebuilding of the engine itself</td>
</tr>
</tbody>
</table>

Four out of 13 points from the ESC –cycle were used as points of load in the tests (Table 6). The points were selected based on lowest possible standard deviation of fuel consumption measurement results, because as accurate values on fuel consumption as possible were sought for. In addition to fuel consumption, emissions were also measured (HC, CO, CO2, NOx) in all tests. The complete ESC –cycle was used in some of the tests, especially when it was intended to measure particle matter (PM).
Table 6. Load points for the reconditioning programme.

<table>
<thead>
<tr>
<th>Number of the ESC-point</th>
<th>6</th>
<th>9</th>
<th>3</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>r/min</td>
<td>1300</td>
<td>1550</td>
<td>1550</td>
<td>1800</td>
</tr>
<tr>
<td>torque [Nm]</td>
<td>830</td>
<td>270</td>
<td>540</td>
<td>740</td>
</tr>
<tr>
<td>load %</td>
<td>75</td>
<td>25</td>
<td>50</td>
<td>75</td>
</tr>
</tbody>
</table>

The results of the reconditioning were not quite what had been expected. This engine, with a mileage of 700,000 km, was already when arriving for the tests in quite good condition considering fuel economy and exhaust emissions. The most significant maintenance measure concerning fuel economy was the replacing of the faulty thermostat. The temperature level of the coolant rose to its planned level along with the replacement of the thermostat. This could also be clearly seen in fuel economy. The fuel consumption decreased by 1.5 – 3.7% in the four chosen points of load. All the maintenance performed after the replacement of the thermostat increased fuel consumption to some extent. The results concerning emissions were parallel; a small increase was also noted in emissions.

Based on the results, there is no point in rebuilding a high mileage engine without a clear reason (do not fix something that is not broken). It is worth reminding that the attained results only apply on the measured type of engine, or actually only on this individual engine. The results can although probably be transferred to other individuals which have received normal maintenance. Maintaining the engine on time is a necessity for the durability of the engine. The importance of oil change should still be emphasised, since impurities accumulated in old oil adds to the wear and tear of the engine.

The obtained results are rather favourable from a bus operator’s perspective, since even an engine of that high mileage has a good fuel economy and does not need expensive repairs. The importance of a properly functioning thermostat could although be seen from the results. The results also show the importance of a well functioning cooling system in general.

Retrofitting

A Volvo VEC – (Volvo Emission Control) system was mounted on VTT’s own Euro 2 – certified DH10A – test engine. The VEC –system is a combination of a particle filter (CRT= Continuously Regenerating Trap, a combination of oxidation catalyst and particle filter) and recirculation of exhaust gases (EGR). The VEC uses a so called low pressure cooled EGR –system. The recirculated particle free exhaust gas is taken after the particle filter, cooled down and fed to the suction side of the compressor using a valve system (STT).

The VEC –measurements were made using the static ESC –cycle because it was not possible to use VTT’s transient engine dynamometer for the tests. When it comes to emissions, the obtained results were good. HC –emissions decreased by over 90% and CO –emissions by 70 - 98% compared with the baseline engine configuration. NOx –emissions were close to the Euro 5 – level, a reduction of some 65%. Particle emissions decreased by some 90% compared to the baseline engine, and ended up on a level which is half of the
issued Euro 4 and 5 limit value. The VEC –system increases fuel consumption by some 4 –
7%. The VEC –system should in addition to the ESC -cycle also be tested using the
transient ETC –cycle for official results agreeing with the instructions of the Directive. The
system would supposedly also have worked in the ETC –cycle.

The obtained results indicate that the engine achieves at least the Euro 4 –limit values, just
as the manufacturer proclaims. The increased fuel consumption is reasonable considering
the significant emission reductions. From an environmental point of view, retrofitting can
increase the service life of an engine considerably.

Summary

The results of this part of the research can, as whole, be summarised as follows. Even after
being driven a lot, the Volvo DH10A engine is in good working condition and it is
therefore not gainful to recondition it without an evident reason. The VEC –system
provided by Volvo seems to, at least under laboratory conditions, work exceptionally well.
Based on received results, it seems to be profitable to install the VEC –system even on
engines of this type without a reconditioning. No after-market technologies for fuel saving
(additives, accessories) have proved to have any measurable effect on fuel consumption.

3.9 AUTOMATED LOAD DETECTION FOR TRUCKS

General

Several applications which utilise information technology and data obtained from, e.g., the
CAN –data bus were thought up during the integrated fuel savings project. An active
driver’s aid device was, for instance, developed in the bus part of the project. A system for
automated detection of slipperiness and an automated load detection system were in the
first place developed for trucks. Both systems could also be used in buses, the load
detection system perhaps with not that good results. For buses the problem is the small
payload weight in proportion to the mass of the vehicle.

The development of the slipperiness detection system (LIUTU) was carried out as a
separate project in 2005. The slipperiness detection system is based on measuring the slip
of the tracting axle using data from the CAN –data bus. When the slip is put into
proportion with the transferred power using a special algorithm, an indication of the
traction between the tyre and the road is attained. The illustration in Figure 35 shows an
outline of the complete slipperiness detection system.

The load detection system (KUOTU) is also based on analysing data from the CAN –data
bus. It is important to know how much load is carried when studying fuel efficiency.
Simply just storing fuel consumption values does not give a correct picture of the fuel
economy, since a fully loaded truck consumes more fuel than an empty truck. When both
fuel consumption and the amount of payload is known, the fuel economy for a certain
performance can be proportioned to the load, in other words litres per ton kilometre.
It has not previously been possible to measure the load without installing additional sensors. Photocells have been used on buses for estimating the exiting ridership and for instance pressure sensors connected to the air suspension on trucks. There are numerous useful applications for combining the load data with speed-, trip- and fuel consumption data. The EMISTRA –follow-up system, for instance, needs data in the form of litre per ton kilometre.

**Development work of the load detection system**

A series of measurements for verifying the load- and slipperiness detection methods were carried out in February 2005. The measurements were made using a full trailer combination truck rented from Transpoint Oy. The vehicle had a CAN –data bus accordant to the FMS –standard. The vehicle was instrumented for data collection, with among others, a data recorder for recording the driving event in a format accordant to the FMS –standard, a GPS –receiver for acquiring data on altitude and a camcorder system for recording the weather and road conditions.

Factors for identifying the load (in this case known load), were sought for from data acquired from the CAN –data bus during the test runs (power, torque, speed, fuel consumption, motion state of the vehicle and so on). The intention was to create a deduction algorithm by which the load can be concluded using this data under all driving conditions.
A series of measurements was first carried out in the neighbourhood of Hyvinkää using different loads. The levels of load were empty, half load and full load. All the above-mentioned levels of load were measured both using merely the truck tractor (max. 26 ton) and using a full trailer (max. 60 ton). The real load was determined by weighing the vehicle.

The other series of measurements were emphasised on slipperiness detection. The above mentioned combination was driven between Hyvinkää and Mikkeli using a constant load. The roadway at an emergency airfield in the neighbourhood of Mikkeli was intentionally frozen here and there in order to simulate black ice.

The processing of the collected data from both the load- and slippery detection tests was performed afterwards. The team succeeded in creating working algorithms for both of them. The power delivered by the engine is used for overcoming driving resistances and for changing the vehicle’s potential and kinetic energy. The tests proved that by constantly computing the energy balance of a vehicle, the weight of the load can be recognised rather exactly.

Figure 36 shows the results for the automated load detection system from three parallel test drives. The result was actually surprisingly good, because it was possible to determine the weight of the load with an accuracy of some 5% at all levels of load. By further development of the computing it might be possible to still improve the accuracy. An accuracy of 5% is although sufficient for following up energy efficiency. VTT has filed a patent application for the load detection system.

![Figure 36](image-url)
3.10 DEVELOPMENT OF A FUEL CONSUMPTION AND ENVIRONMENTAL TRACKING SYSTEM

The Finnish Transport and Logistics Association, the Ministry of Transport and Communications, the Ministry of Trade and Industry and the Ministry of Environment made an agreement on fuel savings for trucks and vans for the years 2003 – 2005. The agreement presumes a follow-up of the realisation of the agreement.

A reporting system signifies in this case a system based on information technology which companies can utilise when complying with obligations of the agreement. Progress in transport companies’ implementation of the fuel saving agreement can also be monitored.

A survey of actual tools and systems was carried out in the preliminary study. Defining follow-up data for fuel efficiency of transports and outlining the general structure of the follow-up system, including its data content, was also done in the preliminary study. In addition, alternatives for energy auditing of transport equipment and definitions for different levels of commitment to the fuel savings programme within transport companies were researched.

It turned up during the survey, that the realisation of the fuel savings program for trucks and vans cannot satisfactorily be estimated without a reporting system. No actual system is directly suitable as a follow-up system. The essential question is how the follow-up system can be implemented in sufficient extent by utilising current systems and without doing overlapping work. Out of current systems, mainly SKALNET and EcoTra contain features which are suitable for a nationwide system.

The transport companies’ nationwide system for fuel savings should be independent of specific data acquisition-, computation- and data transmission systems, i.e. not dependent on a single commercial system. This is best realised when the transport company itself, or a service provider of its choice, takes care of the acquisition, computation and recording of data.

The transport companies’ nationwide reporting system for fuel savings would include a statistic data base, a user data base and an information and training section (upper part of Figure 37). The follow-up system entity would also include, as a continuous process, verification of incoming data, an energy audit, instructions and training. It is important on behalf of the follow-up system’s data content that the fuel consumption and load data is recorded as elaborately as possible. The real changes in fuel efficiency cannot be verified without them.

Based on this project, a nationwide system called EMISTRA was launched in 2005. The system can be used, free of charge, by all Finnish transport companies. More detailed information about the system can be found at EMISTRA’s homepage http://www.emistra.fi.
3.11 CREATING FOLLOW-UP SYSTEMS FOR VEHICLES

General

The goal of this sub-project, carried out by the Institute of Transportation Engineering at Tampere University of Technology, was to develop follow-up systems for monitoring fuel economy of heavy-duty vehicles and to test the systems at chosen transport companies. A generic operations model for following up fuel consumption and factors affecting fuel economy was also prepared. The pilot systems developed in the sub-project were carried out in cooperation with two bus- and two truck companies. The project was realised in the years 2003 – 2005. The sub-project produced a separate report at the beginning of 2006.
The partners were the vehicle depot of Tampere Municipality, Tampere City Transport, Koiviston Auto Oy (bus company) and Transpoint Oy (truck company). EC-Tools Oy served as a subcontractor for Tampere University of Technology. EC-Tools Oy participated in the defining of the pilot systems. It also was responsible for the technical implementation of the pilot systems.

The pilot systems

Pilot systems were created, as part of the sub-project, for five of the partners’ vehicles. The purpose of the pilot systems was to illustrate the possibilities of the follow-up system, to collect data on fuel economy of the partners’ own vehicles and to evaluate factors affecting fuel consumption (Figure 38). Depending on the needs of the companies, additional features for recording operational data was also installed. The development of the pilot-systems continued throughout the project.

Figure 38. Example of a monitoring system developed in the project.
Analysing and reporting of the follow-up data

The follow-up systems produce enormous amounts of data. It is therefore crucial to choose and mark off some of the data in order to bring out the essential. The reporting was also to comply with the emphasis chosen by the companies themselves and the results were to be exploitable using the companies’ own resources. The pilot enterprises represented different lines of businesses and different needs. Different needs were also discovered within the staff. The staff was divided into three groups: senior management, operative staff and drivers. Table 7 is an example of a summary report.

Table 7. Example of a summary report of vehicle fleet.

<table>
<thead>
<tr>
<th>average fuel consumption (l/100km)</th>
<th>average speed (km/h)</th>
<th>number of brake applications (/100km)</th>
<th>total idle time (h,min, %)</th>
<th>fuel consumption when idling (l/ %)</th>
<th>average engine load</th>
<th>average RPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>32.6</td>
<td>35.7</td>
<td>126</td>
<td>106 h 18 min, 61 %</td>
<td>112.3</td>
<td>9 %</td>
<td>43 %</td>
</tr>
<tr>
<td>42.4</td>
<td>26.1</td>
<td>979</td>
<td>31 h 45 min, 35 %</td>
<td>73.8</td>
<td>12 %</td>
<td>40 %</td>
</tr>
<tr>
<td>40.5</td>
<td>54.9</td>
<td>95</td>
<td>50 h 0 min, 29 %</td>
<td>136.2</td>
<td>5 %</td>
<td>41 %</td>
</tr>
</tbody>
</table>

The reporting was improved by enhancing the user-interface of the web pages. Monthly reports aimed for different groups of the staff were created for supporting it. Individual feedback reports, which could be used as part of the incentive scheme, were created for the drivers. The drivers can this way monitor their own performance. The driver’s results are compared both with his own results of previous months and with the results of the control group, which is made up of other drivers’ results.

The drivers’ reports describe driver-specific key figures. The drivers are organised in the report according to their driving style index. The index is formed using normal distribution, which means that both placing compared to other drivers and how much the obtained key figures diverge from the average values affect the colour the driver receives. The drivers’ reports are coloured using index-specific conditions so that the best drivers are green, the average ones black (major group) and the worst read (Figure 39).

Figure 40 shows an example of how the driving style index of a driver has improved. The feedback report that is given to the driver (Table 8) shows the driver’s own key-figures in proportion both to those of the best one in the control group and to the average driver.

When driving vehicles equipped with manual transmissions, the most common reason for poor fuel economy is the driver’s way to use the gears. This is shown as the use of too high rpms. A driving-profile picture was produced in order to depict this. The picture shows the driver’s own level of performance compared both to the group’s average value and to the best driver of the group (Figure 41).
Figure 39. Example of drivers rating from management’s summary report.

Figure 40. Example of drivers’ performance index trend.
Table 8. Example from drivers’ feed back report.

<table>
<thead>
<tr>
<th>DRIVER FEED BACK</th>
<th>OWN</th>
<th>Company average</th>
<th>Best</th>
</tr>
</thead>
<tbody>
<tr>
<td>fuel consumption avg (l/100km)</td>
<td>40.2</td>
<td>40.5</td>
<td>36.5</td>
</tr>
<tr>
<td>speed avg (km/h)</td>
<td>58.1</td>
<td>54.9</td>
<td>51.2</td>
</tr>
<tr>
<td>usage of brakes (#/100 km)</td>
<td>56</td>
<td>95</td>
<td>96</td>
</tr>
<tr>
<td>idle fuel (%)</td>
<td>5 %</td>
<td>5 %</td>
<td>3 %</td>
</tr>
<tr>
<td>idle time (%)</td>
<td>29 %</td>
<td>29 %</td>
<td>14 %</td>
</tr>
<tr>
<td>time in over revs 1660 (%)</td>
<td>19 %</td>
<td>8 %</td>
<td>2 %</td>
</tr>
<tr>
<td>index</td>
<td>62</td>
<td>50</td>
<td>72</td>
</tr>
</tbody>
</table>

Figure 41. Example of driver’s rpm utilisation profile.

Conclusions

The demand for follow-up systems is increasing

The progression of the society and the fact that both national and international agreements and regulations are becoming stricter, have lead to the requirement for improved fuel efficiency and more environmentally friendly vehicles. Driver- and vehicle specific follow-up systems make economic measures, related to fuel savings, possible for transport companies. Advanced follow-up systems can be compulsory requirements of transport customers and -chains. Recording data concerning fuel consumption can also be linked to be part of actual/developing transport chains or operations guidance systems. The use of follow-up systems varies
Active transport companies are well aware of the features of these systems and know how to exploit the data – the use of these systems is also regular. Enterprises representing the other extreme do not pay much attention on monitoring the fuel consumption. The companies’ vehicles might be equipped with fixed on-board computers, installed by the manufacturer, but consumption data is not systematically monitored or put to use.

**Follow-up systems are available**

There is an adequate amount of different types of follow-up systems on the market. Vehicles are nowadays often equipped with fixed on-board computers, which make the most fundamental monitoring of fuel economy possible. Separate and more extensive systems produce considerably more comprehensive information on fuel economy and circumstances connected to it, such as the driver’s driving style. These systems can also be customised for the customer’s specific needs.

**Economical grounds for follow-up systems exist**

Follow-up systems do not improve fuel economy, but factors influencing fuel economy can efficiently be discovered by the use of one. Concrete measures taken based on the discoveries can improve the fuel economy. This way the company can cut expenses. The effect on fuel economy caused by, for instance, bad driving habits can be several percent.

**The implementation of follow-up systems require commitment**

The implementation and continuous exploitation of follow-up systems require commitment from the staff – and also by the management – to a new operations model. The commitment requires training, and even shaping of attitudes. It has been noted, that drivers are not always that well disposed to follow-ups, but at least in this project the feedback on the driving- and fuel economy data handed out to them was positive.

Figure 42 shows a generic operations model for organising the monitoring of fuel economy in a truck- or bus company.
Figure 42. A generic model for introducing a fuel consumption monitoring system to bus and truck companies.
3.12 OPTIMAL DRIVING STYLE FOR HEAVY-DUTY VEHICLES

Buses

The goal of this stage was to lower the fuel consumption and emissions of buses and to improve the accuracy and standard of service of public transportation by developing its operations. This goal is reached by defining an economical “driving rhythm” for every line, by developing the logics of the driver’s aid device and by supporting the development of technical alternatives. The outcome could be improved fuel economy and higher standards of service, which for one increase the use of public transportation and this way saves even more energy.

Driving cycles are needed for comparing the technical features of different busses. These driving cycles simulate actual typical driving as well as possible, but they are performed under laboratory circumstances. There are not many of these cycles. The most well-known in Europe is the German Braunschweig –cycle. There was no measured data on the suitability of using this cycle for describing typical Finnish driving.

Detailed recorded information on Helsinki City Transport’s (nowadays Helsinki Bus Company) urban busses, collected by VTT in the 90’s, was analysed in the first part of the project. This driving cycle material contains data on 3,000 round trips. The data was recorded at one-second intervals (trip, time, speed, bus stops, halts, fuel consumption, ridership). As a result, three driving cycles typical for Helsinki were created (see 3.1.). The cycles simulate downtown driving, combined downtown- and “orbital road” driving and combined suburban- and “orbital road” driving. The part of the Helsinki –cycle describing downtown driving is very much similar to the Braunschweig –cycle (Figure 43). The Helsinki –cycles make it possible to compare busses in different types of metropolitan driving. They have also been used as test cycles in other sub-projects of the research integrate for fuel savings.

There are notable differences in fuel consumption of buses between different runs. Figure 44 shows the driving between the same stop spacing on two different occasions. The difference in fuel consumption is double, 48 l/100km compared to 95 l/100km. Even though a big part of this difference is made up of inevitable traffic situations, the right driving style still plays a big role on fuel consumption, especially in metropolitan areas. Factors which cause these differences in fuel consumption were researched in this part of the project. The results of the analysis are, among others, put to use in another sub-project when developing the driver’s aid device.

An “unnecessary” high momentary driving speed consumes energy in vain. The essential increase in fuel consumption is due to the acceleration phase. At what speed the steady driving is done does not matter that much. For instance the one cycle consuming a lot in Figure 44, accelerated up to the speed limit even though shortly after having to brake because of the traffic lights. By proactive driving it is possible to cut these “peaks” in the cycle, and perhaps even avoid stopping, which saves energy and makes the trip more enjoyable for the passengers. The amount of energy used for accelerating the vehicle and
accumulating kinetic energy goes to waste every time the speed has to be reduced by using the brakes. Even though the traffic situation does not always allow for optimal driving, fuel can still be saved in case one drives as economically as possible whenever there is a chance for that.

Figure 43. Helsinki downtown bus cycle (Helsinki 2).

Figure 44. Cycles with high and low fuel consumption.
When screening the data, it was noticed that the lowest fuel consumption is attained at 50 km/h, when driving at a steady pace. At low speeds the need for energy is small when changes in speed occur, but at higher speeds even a slight change in velocity requires a lot of energy. When it comes to kinetic energy, a change in speed from 55 to 60 km/h coincides with a change from 0 to 24 km/h. The difference in fuel consumption is even bigger, mainly due to the increased air resistance.

Data from the Helsinki City Transport’s travel card system makes it possible to statistically evaluate events on various bus routes. This way it is possible to anticipate and describe various traffic situations. This again can be added to the control logics of the driver’s aid, thus making adaptation to changing traffic situations better.

**Delivery trucks**

VTT recorded driving cycle data (trip, time, speed, halting places, halts, fuel consumption) in the 90’s of a delivery truck performing normal delivery service. Data was gathered from over 100 hours of driving. Based on the data, street sections which were frequently used for delivery services were identified. Driving profiles were then created for these street sections. Characteristic features of a favourable driving style were studied using the driving profiles. The obtained knowledge was combined with that attained during the bus studies.

Clear differences in fuel consumption were noticeable between different runs on the same road sections, as with the buses (Figure 45). Differences in fuel consumption between different runs with the delivery trucks were although noticeably smaller than with buses. Several reasons explain these differences; for buses the driving route studied in detail was shorter (less than 1.5 km) than the one of the trucks (over 2 km), in the case of buses the driver varied from time to time, but the delivery truck was primarily driven by the same driver.

![Speed profiles for a delivery truck](image)

**Figure 45.** Speed profiles for a delivery truck. Highest and lowest fuel consumption for a selected street section.
4 HOW TO AFFECT FUEL ECONOMY?

This part consists of hints for the operators of heavy-duty vehicles. Methods for affecting fuel economy by purchasing, using and maintaining vehicles are covered.

Selecting a vehicle

- The vehicle should always be dimensioned based on actual usage-/capacity demand. An oversized vehicle consumes more fuel and increases expenses by and large.

- Weight is one of the most essential factors affecting fuel consumption. The dead weight of trailers and vehicles should be minimised. An extra 1,000 kg in weight, either as dead weight or as load, adds some 0.7 l/100 km in fuel consumption for a truck-trailer combination in highway driving. In dynamical urban driving the comparable value for buses is some 2 l/100 km per 1,000 kg.

- The efficiency of the engine depends on the level of load so that the efficiency is at its best at a rather high level of load. Therefore the principle for dimensioning the engine should be that the vehicle can cope reasonably with its normal tasks. An excess reservoir of power can easily add 5% to fuel consumption.

- A manual transmission is clearly more efficient than a traditional automatic transmission equipped with a torque converter. A robotised manual transmission could be a good compromise between fuel economy and comfort.

- Differences in fuel economy between different makes might be remarkable, even up to 10 – 15%. The retailer should provide reliable data on typical fuel consumption values for the vehicle in l/100 km. The minimum specific consumption for the engine, given in g/kWh, does not by any chance represent the fuel consumption of the whole vehicle. The actual fuel consumption is also affected by, among others, the transmission and gear ratio, the mass of the vehicle and the aerodynamics.

- Most retailers have access to software by which the selection of a vehicle for a specific task can be optimised. The most suitable engine size and gear ratio can, among others, be estimated using such software.

- Attention should be paid on the vehicle’s aerodynamics. An air deflector installed on the roof of the truck can reduce the fuel consumption by over 5%.

- There are differences between tractive resistances of truck trailers. Based on preliminary results, a 5 axle (single wheels) trailer travels more lightly than a 4 axle (twin wheels) trailer. The fuel consumption of a combination with a 5 axle trailer is...
some 5% lower compared with a combination with a 4 axle trailer. A semi-trailer truck of the same weight as a full trailer combination truck consumes less fuel.

**Fuels and lubricants**

- An engine recognises the input amount of energy, not the volume of the fuel. The fuel consumption, measured in litres, is at its lowest when using summer quality diesel fuel. Availability and securing of its functionality pretty much determine the fuel of choice. It is economically lucrative to use fuel of sufficiently good cold features, but there is no point in using fuel with unnecessarily good cold features.

- It is possible to save 1 – 2% in fuel consumption by choosing the right kind of engine oil. The recommendations of the manufacturer should always be followed. The oil with the lowest viscosity should be chosen among the recommended oils. In addition to viscosity, the quality of the base oil and the used additives affect the oil’s friction properties.

- The effect of transmission oils on fuel consumption is very small. Small difference although emerge between the oils under cold operating conditions. By choosing the right lubricants, it is ensured that damages do not occur in the transmission components, not even under extreme operating conditions.

**Tyres**

- The effect on fuel consumption caused by different types of tyres can easily be over 5%. Differences occur due to the framework and patterning of the tyre and depending on how worn-out the tyre is. Generally speaking a worn-out tyre consumes less fuel than a new one. HOWEVER, SAFETY SHOULD NOT BE COMPROMISED FOR FUEL EFFICIENCY!

- Due to safety aspects, it is not always possible to choose the most economical alternative. On the other hand, there is no point in using too harsh patterning in summer time. Re-grooving of a worn out tyre is economically lucrative. Re-grooving can at its best add up to 25% to a tyre’s operating life while it is at its most economical.

- The frame of the tyre can affect the fuel consumption by some 1%, regardless of patterning or how worn-out the tyre is.

- The right tyre pressure maximises safety and minimises the fuel consumption.

**Maintenance of the vehicle**

- Vehicles should be kept in good repair and be regularly serviced. This way as low fuel consumption as possible is ensured, while exhaust emissions remain low.
• A properly maintained high mileage engine can be in very good condition. There is no evident reason to recondition or renovate a working engine “just in case”.

• Different auxiliary devices and additives claimed to lower fuel consumption are available on the market. The probability for gaining true fuel savings by the use of them is small.

• Solutions and devices provided by the manufacturer, for instance retrofitted exhaust cleaning systems, can safely be used for updating the vehicle’s performance.

The driver and the driving style

• A motivated driver is usually a good driver. The difference between a good and a bad driver, measured in fuel consumption, can be up to 30%.

• The driver’s work can be made easier by the use of technical aids. An example of this is the active driver’s aid device for buses, developed under this project and estimated to save 5 – 15% in fuel consumption.

• It is possible to create righteous drivers’ driving style indexes which take into account the features of both the vehicle and the driven route. Possible reward systems should be fair.

• Different training programs for economical and anticipatory driving are available to drivers.

• Unnecessary accelerating and braking with heavy-duty vehicles increase the fuel consumption substantially. It has been shown that jerky driving styles can even double the fuel consumption of an urban bus.

• Speed essentially affects fuel consumption. Lowering the speed of a truck-trailer combination from 90 to 80 km/h will reduce fuel consumption by some 20%.

Follow-up systems

• It is lucrative for vehicle operators and transport companies to invest in follow-up systems by which the performance of individual drivers and vehicles can be monitored.

• By monitoring vehicle-specific fuel consumption, it can be ensured that defects increasing fuel economy do not occur.

• By monitoring driver-specific data it is possible to; for instance, motivate drivers to achieve as good results as possible using different reward systems or to guide the less well performing drivers into training.
- The follow-up systems used by companies should produce reliable data on mileage, amount of load (ton kilometres) and consumed amount of fuel. An efficient follow-up system is required for estimating the outcome of rationalisation actions on the company’s fleet and operations.
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Tekes – Finnish Funding Agency for Technology and Innovation

AKE – Finnish Vehicle Administration

Ministry of Transport and Communications

YTV - Helsinki Metropolitan Area Council

Division of Planning at Helsinki City Transport

Neste Oil, Base Oils

Neste Marketing

Helsinki City Transport/Helsinki Bus Company

The Public Works Department of Helsinki

Tampere City Transport

Municipality of Tampere, vehicle depot

Pohjolan Liikenne

Kabus

Transpoint

The Volvo foundation of bus traffic

AC Electric Vehicles

Buscom

Taipale Telematics

VTT
REPORT REGISTER

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