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Simulation of Energy Consumption and Emissions from Rail Traffic

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Publication date:
2005

Document Version
Publisher's PDF, also known as Version of record

SIMULATION OF ENERGY CONSUMPTION AND EMISSIONS FROM RAIL TRAFFIC

ARTEMIS

By Author(s)

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Workpackage 700: Emission Estimating Methodology for Rail Transport

Assessment and reliability of transport emission models and inventory systems

Project funded by the European Commission within The 5th Framework Research Programme

DG TREN Contract No. 1999-RD.10429

Deliverable No. D7a

Report No : MEK-ET- 2005 – 04

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25, February, 2005

ISBN 87 – 7475 – 328 – 1

PUBLICATION DATA FORM

<table>
<tr><td colspan="2">1 UR (1st author)
Dept of Energy Engineering, Tech. Univ. of Denmark</td><td>2 Project No</td><td>**3 Report No**
MEK-ET- 2005 – 04</td></tr>
<tr><td colspan="4">4 Title
Simulation of Energy Consumption and Emissions from Rail Traffic Evaluation</td></tr>
<tr><td colspan="3">5 Subtitle</td><td>6 Language
English</td></tr>
<tr><td colspan="3">7 Author(s)
E. Lindgreen, S. C. Sorenson</td><td>8 Affiliation
DTU</td></tr>
<tr><td colspan="3" rowspan="2">9 Sponsor, co-editor, name and address
European Commission</td><td>10 Contract
1999-RD.10429</td></tr>
<tr><td>11 Publication date
28, February, 2005</td></tr>
<tr><td colspan="4">12 Notes
ISBN 87 – 7475 – 328 – 1</td></tr>
<tr><td colspan="4">13 Summary
This report describes the methodology used in the ARTEMIS rail emissions model. The approached used is a matrix of operating conditions, speeds and accelerations, for which basic parameters are used to calculated the resistance to motion of trains. Four types of resistance are included: rolling, aerodynamic, gravitational and acceleration. A necessary element in the calculation is the driving pattern, that is, the distribution of speeds and accelerations for typical operation.

In the report, data are analyzed to provide operation condition distributions on both a spatial and temporal basis. The calculation procedure is evaluated with respect to resolution of operation conditions, and then evaluated by comparison with experimental data for a variety of passenger and goods trains. The results indicate that the energy consumption from modeling approach is valid to better that 10% for known operating characteristics. Emissions are calculated from the energy consumption using average fuel based emissions factors and electrical production emissions factors.</td></tr>
<tr><td colspan="2">14 Key Words
Rail transport, modeling, energy consumption, air pollutant emissions</td><td colspan="2">15 Distribution statement
FREE</td></tr>
<tr><td>16 No of pages
137+appendices</td><td>17 Price
FREE</td><td>18 Declassification date</td><td>19 Bibliography
YES</td></tr>
</table>

Abstract

A model for simulation and calculation of energy consumption and air pollutant emissions from rail traffic is developed, evaluated and described. The model is designed especially for simulating a simplified transport pattern, which is divided in to several elements of an operation matrix. Each element is bounded by an interval related to acceleration, and an interval related to speed. A transport pattern can be divided into a comparative low number of intervals related to speed, while it's necessary to apply several numbers of intervals related to acceleration in order to receive a realistic result. A normal haulage can for instance be divided into tree or four intervals of speed, and ten intervals related to acceleration. This may give about 30 to 40 elements.

This means that by application of the model a more simple transport pattern can be used instead of the usual often very detailed total transport patterns. This "block-method" is simple, mostly because a transport pattern divided into different intervals of speed and acceleration can be constructed much easier and without use of a measured pattern of transport. In addition, it is possible to emphasize the tendencies and relationships, which should be analyzed and calculated. The model can simulate both in relation to time spent (time distribution), and to distances run (position distribution). The approach can be applied to a variety of scales, from an individual train to a national average.

Given the speed and acceleration of a train, the operating resistance due to rolling resistance, aerodynamic resistance, gradients and acceleration can be calculated from basic principles. The energy consumption and emissions are then related to fundamental technical parameters, which depend on the train type, composition. In principle, the model can be applied to any type of train by modifying a few constants.

The basic element of the calculation is the determination of the amount of energy used to move the train wagons themselves. The final energy consumption is then determined by the drive train efficiency, which depends on the type of drive unit. The standard regulated emissions of CO, HC, NO_x, and particulate matter are determined from the fuel consumption and fuel specific emissions factors in the case of diesel powered trains, or electrical energy consumption and national electrical energy generation emission factors for electric trains.

A calculation based on a normal, measured transport pattern usually has measured speeds or distances recorded at intervals of one to ten seconds. The operation matrix principle, however, is based on the percentage of each operation element in relation to the total transport pattern, i.e., a statistical distribution of operating conditions. The assumption is made that the operation in individual elements is independent of

operation in any other element. That is, there is no historical effect, and the elements may be analyzed in any order.

The model is designed for a transport pattern (transport distribution) selected by the user. The model is designed for evaluation of the driving matrix because it provides a comparison of the two methods of calculation. A series of tests were conducted to test the principle, in which second-by-second calculations were performed for a real transport pattern and the results compared with results obtained by calculations based on the load pattern for the transport in question.

The overall goal of the model was that the calculated energy consumptions and – emissions did not deviate more than about 20% from experimental values.
The model and the principles have been tested by comparison between the calculated energy consumption and emissions for a series of selected transports on one side and corresponding data for the same transports calculated by DSB on the other. This has been performed for 13 transports with different goods and 19 transports with different passenger trains.

For the passenger trains the deviations relative to the figures of DSB were on the average 7-8%. The largest discrepancy is close to 15%, which is also satisfactory. For the goods trains the average deviation from the calculated figures of DSB was 15%, with single discrepancies of up to 25%. The fact that the deviations for the goods trains are approximately twice those for the passenger trains may be due to that the uncertainties with regard to data for amount of goods and to resistance are considerably larger for the goods trains. Whereas the details of wagon content are known for the passenger trains, this is not the case for the goods trains. Only the amount of goods, the total weight of the wagons and the length of the train are known. Altogether the model can, however, be considered to carry out the calculations satisfactorily.

Subsequently, the model has been applied for analysis of several actual problems connected with transport by train and the relation of these to energy consumption and – emissions. For evaluation of the transport characteristics of different types of trains, the transport and the transport distribution for these trains (InterCity and ”regional” passenger trains and goods trains) have been analyzed.

First, the influence of the number of stops on the energy consumption and emissions has been analyzed for a train. Simulations have been performed for three different types of trains on the Coast Line between Elsinore and Copenhagen H. A non-stop express train consumes 50-56% less energy than a conventional ”regional” train stopping at all stations. Conforming to this, a train at peak hours having a limited number of stops consumes 20-36% less energy compared than the conventional ”regional” train.

Second, the influence of the quality of the transport has been investigated, by simulating two goods transports with MF train sets from Copenhagen H to Høje Taastrup. The first transport is without interruptions from e.g. signals or other trains. The second is less steady, with more pull-ups and subsequent accelerations during the run. The unsteady transport used 40-60% more energy than the more steady one. Thus, signal stops, decreasing speed and poor capacity result in this case in an increase in energy consumption of app. 50%.

Third, the influence of maximum speed has been investigated. Simulations have been carried out in and intercity train for three different maximum speeds of 140, 160 and 180 km/h, between Copenhagen H and Korsør. The pattern of transport is steady for all maximum speeds, i.e., no significant speed changes or other patterns of interruption. A decrease in speed from 180 to 140 km/h results in a decrease in energy consumption of 20-25%, and a decrease in speed from 180 to 160 km/h gives a decrease in energy consumption of 10-14%.

Fourth, the reduction in energy consumption through covering the wagons of an ordinary freight train to become homogeneous has been calculated. On the average the reduction is 2-6%, which must considered low compared to the problems of carrying out the covering in an actual situation.

Further, a series of similar simulations have been carried out for different types of trains and train transports. This includes both electric and diesel trains, ranging over almost all kinds of train types (IC, IC-lightening, urban trains, freight trains etc.)
This has been done in order to provide a kind of statistic basis for energy consumption and emissions for different types of trains.

1. Introduction

Railways play a significant role in the European transport network. The railway network for the EU 15 countries encompasses on the order of 160 thousand km. This represents a significant transport resource as well as a large investment of the part of society. The development of the future transport network and the wise use of resources require that this network be utilized in an appropriate manner.
A significant factor in the evaluation of a part of the transport network is its contribution to the problem of air pollution. This can be important on both the local level (HC, CO, PM and NO_x) and an international scale (CO_2, SO_x, NO_x). Since there is interest in evaluations on different levels, it would be advantageous to have calculation (modeling) methods for air pollution from rail transport that could be used at a variety of spatial levels. The advantages with this approach are comparison consistency and reduced development time. When one uses different models for different spatial scales, there is the risk of bias between the two models, unless special care is taken in model development. A common model encompassing a range of spatial scales should reduce this risk. If a model can be produced to cover a range of spatial scales, there should be a smaller amount of time required for model development than in the case of several models for several spatial levels.

Another goal for the development of a model for railway emissions is that it be technologically based. What this means is that the fundamental physical processes determining the energy consumption and air pollution emissions should be an integral, identifiable part of the model. There are several advantages with this approach. One of them is that this makes the model easier to upgrade in the future. Technological improvements in areas such as aerodynamics, train weight, rolling resistance, engine efficiency or emission control can be readily incorporated into future calculations. This is because the influences of these parameters on operation and therefore emissions and energy consumption have been correctly included in the model. Cross influences that result from curve fitting (black box) approaches are eliminated with this approach. Rather than generating an entire new model when technical improvements appear, only a few readily identifiable parameters need be changed. This approach has been very successful in the application of simulation models for engine control systems (Hendricks and Sorenson, 1990)

Changes in operating conditions can also be incorporated in a correct fashion, since the influences of variables such as acceleration and speed are correctly modeled from a physical point of view.

2 Data

2.1 Types of trains analyzed

The purpose of the analysis is to illustrate a series of operating patterns with the goal of construction of models for the way in which these types of train operate. Therefore, it is necessary to have a significant number of train types represented. In addition, there should be a statistical relevance of the analysis. That is, it is advantageous to have a large database.

The driving pattern data were made available from the Danish State Railways, DSB. Most of these are printouts from the crash logs ("black box"). The information contained here included time, location, speed, maximum speed, ATC-speed and the load on the engine. ATC (automatic train control) is the train's safety system, which is built to intervene if a train goes too fast or if it passes a stop signal.

The data is not logged according to defined intervals of time or location. But the data is logged every time there is a change in operating conditions. This could include a change in traction force, brake pressure, or if the train receives information on new speed limits or such. This represents very detailed measurements, since the length of the train, braking percent and the maximum allowable speed are also included. It was necessary to read the logger data specifically for each individual run, based on time and number of driven km. The measurements for the IC3 (MF) trains are not from the "black box" but are specific measurements, which were recorded every tenth second.

In addition to these results, summaries about which train type and operation conditions were used. That is to say, number of wagons, which kind of traction was used, as well as which stations were involved. Arrival and departure times and number of driven kilometers were included. Information was also available on the number of seats in the train or how many tons of goods were transported, and in both cases, the total weight of the train.

Of great importance is the fact that in many cases, the load collective was available. This is a list over how much of the time the engine operates in its different load/controller steps. Examples of load collectives are shown in Appendix 2 for a goods train and two passenger trains.

All the data was obtained from the Danish State Railway, DSB. The operations occurred over a period from early 1999 to the spring of 2000.

2.2 Description of train types

As mentioned, the models are intended to be used to test and verify the method of calculations and as tools for the calculation of energy consumption and operating characteristics. They will be used to calculate the overall operation data as well as the energy consumption and emissions for these data.

To accomplish this, the crash logs have been used to select operations for different train types. Due to time limits, only a few trains can be analyzed in detail, and it is therefore necessary to select as broad a representation of train types as possible. Overall, there are two general types of trains to consider: Passenger trains and goods trains. They can be subdivided into categories:

2.2.1 Goods trains:

- Post (mail) trains (GP)
- Material trains (GM)
- Regular goods trains (G, GS)

2.2.2 Passenger trains:

- Regional trains (Re)
- Intercity trains (IC)
- ("Lightning") trains (IC-Lyn)
- Express trains (IN, EP)

High-speed trains are not included, since operation in Denmark with speeds over 200 km/h is not yet found. Therefore, only the above types of trains are included in the calculations. An overview of these in found in Chapter 13 (Tables 13.1 to 13.5). From a technical point of view, the energy consumption of high speed trains will be determined by the same factors as all other trains: aerodynamic resistance, rolling resistance, acceleration and gradients. Differences encountered in operation are higher speed, and fewer acceleration periods. Therefore, rolling and aerodynamic resistance will have a greater relative importance that with trains that stop more often. Nevertheless, from a technical point of view, establishment of modeling principles on the above types of trains is adequate to confirm the general approach, which should also be valid for high-speed trains when appropriate data is applied.

2.2.3 InterCity and InterCity "Lightning"

Intercity and "Lightning" trains are operated with IC3 equipment (type MF) and ER. An overview of the equipment covered in this report is found in Appendix 1. For operation with the IC3, the number of train sets in the total train was not available, in most cases two, three or four sets are used, so an average value of 4 was used. Since each set is powered by the same engine, there should not be a great effect of the number of sets. Previous results (MEET report) showed that aerodynamic resistance for trains with more than one set is not strongly affected by the number of sets.

In addition to equipment data, weight and size, an attempt has also been made to cover a many different routes as possible. For the IC and IC-"lightning" it has only been possible to obtain operating data for the runs between:

- København H. - Århus,
- Østerport - København H. - Odense - Fredericia
- København H.- Sønderborg

2.2.4 International train (Express train)

There are only a few of these trains. These trains run from Oslo and Stockholm to Copenhagen via the Coast Route. That is to say, they operate between Elsinore and Copenhagen without intermediate stop. They are relatively large trains with between seven and 11 wagons. In all cases, the locomotive used is the MZ4. The trains are designated IN (InterNord). Most of the wagons are standard Swedish wagons.

2.2.4 Regional train

The regional trains are divided into trains east and west of the Great Belt. This is because different equipment has traditionally been used for these two regions. In the east, conventional trains with locomotives and a number of cars have been used, including a control car at the end opposite the locomotive for operation in the opposite direction. MZ4 and ME are used for locomotive and Bn passenger wagons are used along with the control wagon ABns.
In the west, operation is normally made with the type MR-MRD, which consists of two nearly identical motor coaches. The calculations have been made for a single train set, the most common operational mode. In addition, calculations were made on regional trains on Funen and in South Jutland driven with ER equipment. .
For the regional trains in the east (RØ) calculations were performed for basically all regional train routes on Zealand. That is operation between:

- Copenhagen - Elsinore
- Østerport - Copenhagen H - Kalundborg
- Østerport - Copenhagen H - Næstved – Nykøbing F.

These trips were operated with conventional passenger train equipment consisting of a locomotive and a number of wagons.

.

The regional trains west of the Great Belt (RV) are distributed on the routes:

- Århus - Thisted
- Århus - Ålborg - Frederikshavn
- Århus – Viborg – Struer
- Århus - Grenå
- Århus – Skanderborg - Silkeborg - Herning
- Århus - Fredericia
- Fredericia – Kolding - Esbjerg
- Esbjerg - Struer

All of these are operated with MR equipment.

In addition there is a regional train route driven by the electric train set ER

- Odense - Fredericia

2.3.6 Goods trains

The goods trains have a more mixed character.
With respect to the routes, trains were chosen from the following routes (the train operates between the following towns):

- GB (Copenhagen Goods Yard) - Kalundborg
- GB - Høje Tåstrup
- GB - Ringsted
- Ringsted - Fredericia
- Fredericia - Århus
- Fredericia – Århus - Torsøvej (near Risskov, Århus)
- Århus - Aalborg
- Odense - Ringsted
- Fredericia - Ringsted – Glostrup
- Slagelse - Glostrup
- GB - Køge
- Køge - Næstved
- Næstved - Ringsted
- Næstved - Nykøbing F.

As expected, the goods trains have different shapes and arrangements. Common for all the goods trains, though, is that either MZ4 or ME locomotives are used for traction. An attempt was made to choose a representative and comprehensive selection of goods trains, the first and foremost criterion being a wide range of sizes. Size in this regard

means primarily train weight, number of wagons being the second factor of choice. As Table 13.5 shows, these two quantities are not necessarily proportional. This is due to variations in the load factor.
As mentioned, post trains consist of the same wagon type, which means that the actual arrangement of these trains is known. The wagons here are long, closed 4-axle wagons of the type Habbinss-y. This makes the calculations of the train's physical characteristics simpler, and reduces the uncertainties concerned with the driving resistance values.

2.3 Short description of type of equipment

The following material is a supplement to Appendix 1, where some of the most common types of equipment are described. The material used has been obtained from "DSB-materiel i drift" (DSB, 1996). See also (Lindgreen and Sorenson, 2005)

2.3.1 Locomotives

The locomotive types used are the ME and MZ4. They are used to power regional trains and goods trains. The locomotives have a diesel-electric transmission system. The diesel engine in the MZ4 is more powerful (2685 kW) than in the ME (2460 kW). On the other hand, the ME has alternating current, while the MZ4 uses an older direct current system, which equalizes some of the difference. The diesel engine in the MZ4 supplies power to heating and such, while the ME has an auxiliary motor for such purposes. Both operate with fixed controller steps for regulating power output.

2.3.2 Train sets

The material used for longer range trips are the types: MF (IC3) and ER (IR4). The MF is a diesel mechanical powered unit consisting of three wagons.
The ER is an electrical powered four-wagon train for both longer range and regional traffic. It's internal layout and slow door closing make it better suited to longer-range operation. Both train sets have fixed controller settings, and well as cruise control for regulating the traction force. The cruise control allows the train to maintain a constant speed but allowing free adjustment of torque, without regard to which controller step is engaged. In this case, the conventional loading collective does not exist, since the controller stages are not used in this type of operation.

The third train set used is the type MR, which is intended for regional traffic. The train consists of two nearly identical motor wagons, each with a power of 237 kW (DSB 1). The train used fixed controller steps with accompanying power steps as with the MZ4/ME. This is the only train set that used a diesel-hydraulic transmission.

2.3.3 Passenger wagons

Since most of the passenger traffic in Denmark has been taken over by train sets, the passenger wagon plays a diminishing role in the total passenger transport picture. In the regional traffic east of the Great Belt, regional trains with the traditional type of passenger wagon, type Bn, operate between Copenhagen/Østerport to Næstved/Nykøbing F. and Kalundborg, as well as some few operations on the Coast Line. These trains consist of an ME/MZ4 locomotive + n Bn wagons + one Abns controller wagon, which corresponds to the Bn. The international trains use sleepers, couch and coupé wagons. Most of these wagons are Swedish wagons of standard construction. This type was chosen to be represented by the type B7. This is a relatively heavy wagon with a weight of 44 tons (Lukazewicz, 1995). For comparison, the Bn wagon weighs 36 tons.

2.3.4 Goods wagons

Most goods trains consist of a large number of different wagon types. It is rarely known which types of wagons make up a specific goods train. This was not given for the post trains either, but since the Danish post trains are always composed of the same type of wagon, it is possible to evaluate the characteristics. The preferred type of wagon is the type Habbinss-y. This is a closed, 4-axle goods wagon with a length of 23,24m.

A complete list with data and drawings is given in Appendix 1.

3 Calculation of driving resistance and energy consumption

3.1 Driving resistance

Under ideal conditions, that is steady speed on flat straight stretches, there are two kinds of driving resistance that are important:

- Aerodynamic resistance, F_L
- Rolling resistance, F_R

In actual operation the conditions may be somewhat different. Gradients give rise to extra resistance due to gravitational attraction, and curves cause extra friction between the wheels and the rails. This causes two extra resistances:

- Gradient resistance, F_S
- Curve resistance, F_K

The ability to calculate curve resistance demands a very detailed knowledge of the tracks. Since this knowledge is rarely available, F_K is not considered.
The resistances used are shown in Figure. 3.1.

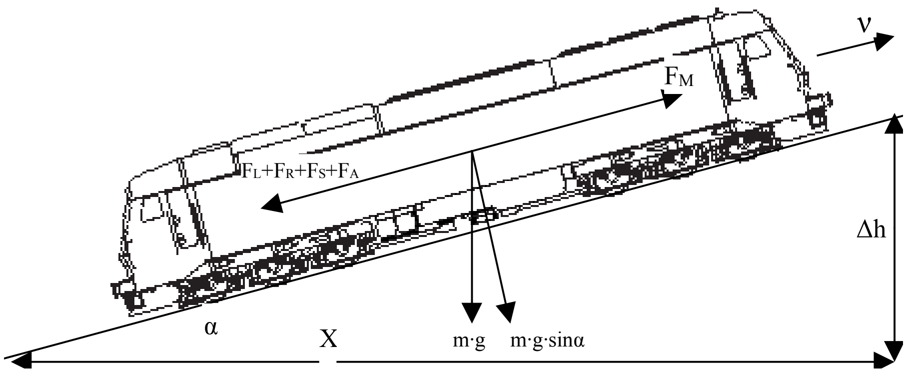


Figure 3.1 Sketch of driving resistances.

Using Newton's 2nd law in the direction of travel, the connection between the driving resistances and motion is given as:

$$m \cdot a = F_M - (F_R + F_L + F_S) \Leftrightarrow m \cdot a = F_M - F_R - F_L - F_S \qquad (3.1)$$

m·a is normally called the acceleration force $F_{A,}$ or acceleration resistance. F_M is the locomotive's traction force at the wheels. Equation 3.1 can then be rewritten:

$$m \cdot a = F_M - F_R - F_L - F_S \Leftrightarrow F_M = F_R + F_L + F_S + F_A \qquad (3.2)$$

The remaining resistances are described in the following.

3.2 The individual driving resistances

The driving resistance of most importance: aerodynamic and rolling, are dependent on a variety of factors. The techniques for calculating these factors and their relative importance for a variety of train types are described in an accompanying report (Lindgreen and Sorenson, 2005). The basic principles are reviewed here.

The aerodynamic resistance is dependent on the frontal area of the train, its shape and its speed. In addition, atmospheric factors as air density and wind direction have an effect:

$$\boldsymbol{F_L} = 0{,}5 \cdot \boldsymbol{\rho} \cdot \boldsymbol{C_L} \cdot \boldsymbol{A_{fr}} \cdot \boldsymbol{(v + v_{wind})}^2 \qquad (3.3)$$

Where: F_L is the total aerodynamic resistance in N
v is the train's speed in m/s
v_{wind} is the (head) wind speed in m/s
ρ is the air density in kg/m^3
C_L is the drag coefficient.
A_{fr} is the frontal area in m^2, often assumed to be $10m^2$.

The rolling resistance is a function of the total mass of the train and the rolling resistance coefficient.

$$F_R = C_R \cdot m_{tot} \cdot g \qquad (3.4)$$

Where: F_R is the total rolling resistance in N
C_R is the rolling resistance coefficient
m_{tot} is the train mass in kg
g is the acceleration of gravity (9,82m/s^2)

The gradient resistance is dependent on the weight of the train and the size of the gradient to which the train is exposed.

$$F_S = m_{tot} \cdot g \cdot \sin\alpha \Leftrightarrow$$
$$F_S = m_{tot} \cdot g \cdot \frac{\Delta h}{x} \cdot 1000 \qquad (3.5)$$

Where: F_S is the total gradient resistance in N
m_{tot} is the train's mass in kg

g is the acceleration of gravity (9,82m/s^2)
α is the angle of the gradient.
Δh is the height difference [m] over the horizontal distance x [m]

It is also possible to use the value of α in radians instead of Sin(α). In the calculation of an operating pattern from point to point, it is not necessary to calculate the gradient resistance for each individual grade. In general, it is sufficient to calculate the height difference at the origin and destination, and use that for the total route. This gives the net gradient resistance. This assumes that the extra power the train uses to force a grade is returned when the train goes down corresponding grades.

Curve resistance is normally not too large. It is one of the smallest driving resistances and since it is very complicated to calculate, and since it requires very detailed route information, it is excluded from further consideration (Friis Hansen, 1991).

Calculation of driving resistance for goods trains.
It is generally much more complicated to calculate driving resistance for goods trains, since they typically have an inhomogeneous composition, and vary greatly in form and appearance (in contrast to a passenger train set, for example). In many cases, goods trains are composed of many different wagon types, each having its own resistance values and frontal area. For a comprehensive explanation, see Lindgreen and Sorenson, 2005.

3.3 Energy consumption

The total energy consumption can be calculated in several ways.
Based on knowledge of driving resistance (first and foremost aerodynamic and rolling resistance), the energy consumption can be calculated by integrating the instantaneous force over the traveled distance:

$$E = \int_{x_1}^{x_2} F_{tot}\, dx \quad \text{That is,} \qquad (3.6)$$

Where F_{tot} is the sum of the driving resistances, that is: F_L, F_R, F_S and F_A. Then:

$$E = \int_{x_1}^{x_2} (0{,}5 \cdot \rho \cdot C_L \cdot A_{norm} \cdot (\nu_{train} + \nu_{wind})^2 + m_{train}(C_R \cdot g + g \cdot \sin(\alpha) + a))\, dx \qquad (3.7)$$

In the case where the velocity is constant, as in a matrix element, the resistances do not change, so.

$$E = \{0{,}5 \cdot \rho \cdot C_L \cdot A_{norm} \cdot (\nu_{tog} + \nu_{vind})^2 + m_{train}(C_R \cdot g + g \cdot \sin(\alpha) + a)\} \cdot (x_2 - x_1) \qquad (3.8)$$

Alternatively, The power, P_e can be calculated as:

$$P_e = \nu \cdot F_{tot} \tag{3.9}$$

Where:

P_e is the power in W
ν is the speed in m/s
F_{tot} is the sum of the driving resistances: F_L, F_R, F_S and F_A.

From this, the energy consumption can be calculated as:

$$E = \int_0^t P_e \cdot dt \tag{3.10}$$

Where:

E is the energy consumption in J
P_e is the power in W
t is the elapsed time in s

If P_e is constant, the energy consumption is:

$$E = P_e \cdot t \tag{3.11}$$

3.3.1 Combustion engine efficiency

As an extension of the above, there are a series of factors, which depend on the specific equipment at hand.

3.3.2 Fuel consumption:

If the brake specific fuel consumption of the engine is known, the flow of diesel fuel can be calculated as:

$$\dot{m} = b_e \cdot P_e / 3600000 \tag{3.12}$$

where:

$\dot{m}$ is the fuel flow to the engine in kg/s
b_e is brake specific fuel consumption of the engine in g/kWh
P_e is the engine power in kW.

From this, the brake thermal efficiency of the engine can be calculated:

$$\eta_e = \frac{P_e}{\dot{m} \cdot H_u} = \frac{3{,}6 \cdot 10^6}{b_e \cdot H_u} \tag{3.13}$$

where:

$\dot{m}$ is the engine fuel flow in k/s
H_u is the lower heating value of the fuel. (assumed to be 42700 kJ/kg).
b_e is brake specific fuel consumption of the engine in g/kWh
P_e is the engine power in kW.

3.3.3 Units for energy consumption

There are several ways to denote the energy consumption and emissions. In comparison between trains and other transport types, consumption in kWh or kJ for example, is not always useful. For these purposes, it is more useful to use weighted parameters in terms of driven km or weight hauled. In general, kJ/ton-km is used for energy consumption and g/ton-km for emission, regardless of the type of train. In this comparison, the tonnage is usually the total weight of the train for calculation purposes and per ton carried for transport emissions.

In addition, a few other parameters are useful, depending on whether a passenger or goods train is being considered.

Passenger train
In addition to kJ/ton-km one can express energy consumption in terms of either passenger transported km or seat km.:

- kJ per passenger km (kJ/pass-km)
- kJ per seat km (kJ/seat-km)

In terms of transport performed, weighting in terms of the number of passengers transported is probably the most useful. The number of passenger km is often known from rail statistics. When looking at individual trains, though, it is usually not known how many passengers they carry. Therefore, from the point of view of individual trains, it is often more accurate to use kJ/seat km. The difference between these two parameters is, of course, the loading or occupancy factor.

Goods trains
In addition to the units of kJ per train-ton km, one can also use:

- kJ per goods-ton km (kJ/goods-ton km)
- kJ per ton km, where the weight is only that of the train wagons and the load, that is the locomotive weight is not included.

Normally weighting according to the tonnage of goods will be of most interest, since the importance of the locomotive will vary from small trains to large train. Locomotive weights are on the order of 80-100 tons per traction unit.

3.4 Emissions

The procedure for calculating emissions depends on whether the train is diesel or electric powered.

If emissions are to be calculated for trains with diesel power, the emissions can be estimated on the basis of the amount of diesel fuel consumed.

For electric trains, there are no significant emissions from the train itself. The emissions must be calculated from the source of electric energy, according to the energy that the train has consumed. The emissions considered are:

- CO_2
- CO
- NO_x
- HC
- SO_2
- Particulate matter (PM)

3.4.1 Calculations for Combustion Engines

Some emissions, such as CO_2 and SO_2 are solely related to the amount of fuel consumed, while the others are related to the engine condition, operating point, and driving characteristics.

The different types of emissions can be approximated by using typical average values (Jørgensen and Sorenson, 1997)

	Emission, g/GJ	
Emission	Spread	Average
CO_2	70000-76000	74440
CO	160-350	246
NOx	1200-1500	1320
HC	44-120	66
SO_2	20-100	75
PM	41-140	76

Table 3.1. Emissions factors for diesel engines in g/GJ fuel energy (lower heating value).

3.4.2 Emissions for electrical operation

The emissions used here are the emissions based on an average of a given land's electricity production. The emission factors are very dependent on the way the electricity is generated. The production must be weighted according to how much of a land's electricity is produced by fossil fuel power plant, nuclear power, and renewable energy, such as wind and water.

Land	CO_2, g/GJ	CO, g/GJ	NO_x, g/GJ	HC, g/GJ	SO_2, g/GJ	PM, g/GJ
Austria	62900	14,5	92,7	16	74,2	6,9
Belgium	94300	16,7	289,4	12,2	533,5	27,2
Denmark	257300	43	811,6	24,7	912,9	62,7
Finland	155100	38,6	307,3	15,6	198	23,4
France	17600	3,2	61	3,2	183,9	7,9
Germany	189700	27,3	306,3	9,4	931,5	56,2
Greece	296400	38,7	393,6	38,9	979,2	62,4
Ireland	212900	33,8	672	44,6	1639,5	74,3
Italy	162500	33,4	551,7	105,3	977,2	41,1
Luxembourg	101900	16,2	90,1	16,9	71,1	3,7
Holland	175700	31,6	281,8	32	185,2	19
Portugal	170400	34	507,1	53,7	1260,7	59,4
Spain	126800	19,4	414,2	16	1235,8	57,8
Sweden	20600	6	42,2	6,6	34,7	3,1
Great Britain	167800	27,4	631,8	20,2	1445,8	69,9

Table 3.2. Emissions factors for electricity production in the EU 15 countries on the basis of GJ electricity produced (Lewis, 1997)

Even these figures are subject to interpretation. For example, in Denmark, waste heat from electricity generation is used in district heating, raising the problem of allocation of emissions to different sectors.

4 Theoretical considerations for driving patterns

This chapter will look at the nature of typical driving patterns. A driving pattern can describe a train operation either as a function of the elapsed time or the number of driven kilometers. Each of these is described with a set of equations that describe the operation in any phase.

In general, there are 4 types of operation that make up a driving pattern: acceleration, constant speed operation, rolling and braking. In addition, there is stop time.

- Acceleration
  The train's speed is increasing. This can be due to start from a station, signal or in connection with a change in speed limits. Some limiting cases would be constant acceleration, constant traction force, or constant engine power.
  During the acceleration, the traction force required is usually significantly larger than the aerodynamic, rolling or possibly gradient resistance.

- Constant speed operation.
  Since the speed is considered constant, the required traction force is equal to the sum of the driving resistances (aerodynamic, rolling and gradient). In model developed here, a minimum acceleration is defined, under which it is assumed that the acceleration is zero.

- Rolling
  Both rolling and braking are portions of the operation where the speed decreases. In the case of rolling, the braking force and the traction force are both equal to 0. That is, it is alone the driving resistances that determine the speed of the train. This condition is useful for measuring the resistance parameters in a so-called "coast-down test".

- Braking
  In this condition the brakes are active. That is, the traction force is 0, while both the braking and driving resistances slow the train down.

As mentioned before, a driving pattern can be expressed either as a function of time (t) or distance (x). Normally the speed is used as the dependent variable.

In the following the nature of the elements of driving patterns will be discussed.

The most important parameters describing a driving pattern; that is, a, v, t and x, are connected through some equations of motion.

In the case of constant acceleration:

$$v_2 = a \cdot t + v_1 = \sqrt{(2 \cdot a \cdot x + v_1^{2}} \qquad (4.1)$$

Where: v_2 and v_1 are the final and initial speeds, respectively
a is the acceleration in m/s^2
t is the elapsed time in s
x is the driven distance in m

For constant speed operation, there is a simple relationship between time and distance:

$$v = \frac{x}{t} \qquad (4.2)$$

Figures 4.1 and 4.2 show the 4 general types of operation. Both figures are individual segments from an operation of a Danish MF train between Copenhagen Central Station and Ringsted:

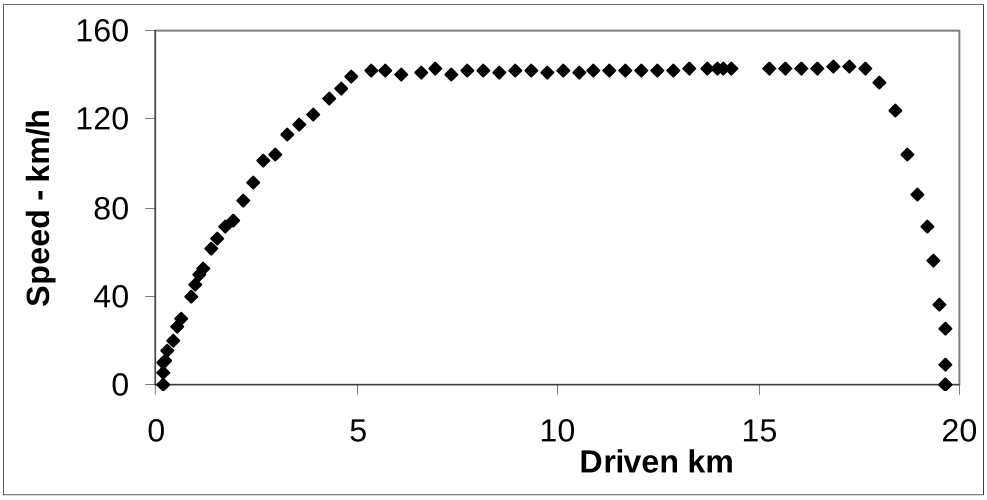


Figure 4.1 Train speed as a function of distance for an MF train.

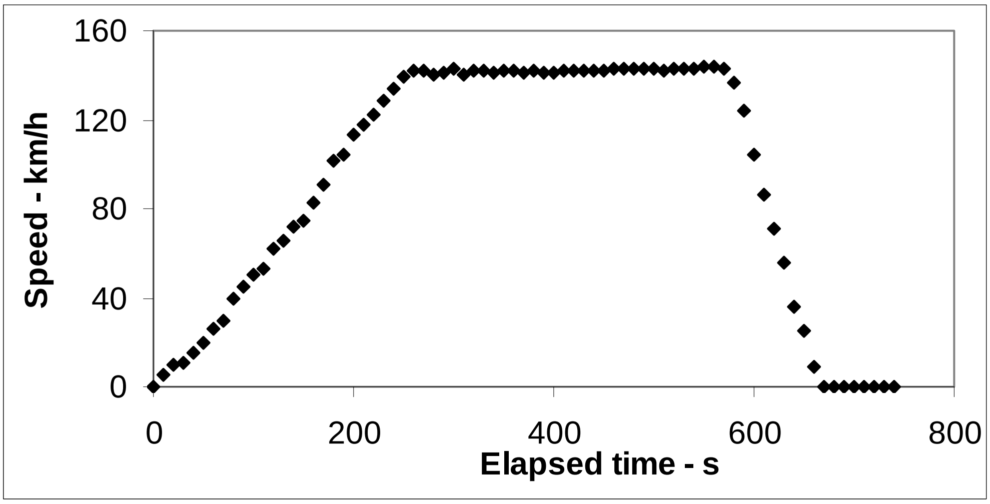


Figure 4.2 Train speed as a function of elapsed time for an MF train.

In this particular element, there are three situations when the train is in motion. The first is the acceleration. On the basis of the distance driven, the velocity has a form of roughly second order dependence on speed, which results from a constant acceleration according to Equation 4.1. Figure 4.2 shows that the velocity is nearly linear with respect to time, indicating a nearly constant acceleration. The average acceleration is about 0.15 m/s^2 in this case.

For the section of operation shown, the speed increases to a roughly constant value of about 140 km/h, which it maintains until braking occurs after about 18 km or 600 seconds. In this case there is no observable rolling, as the speed time profile abruptly shows a linear decrease in the train speed. The magnitude of the deceleration is about -0.44 m/s^2.

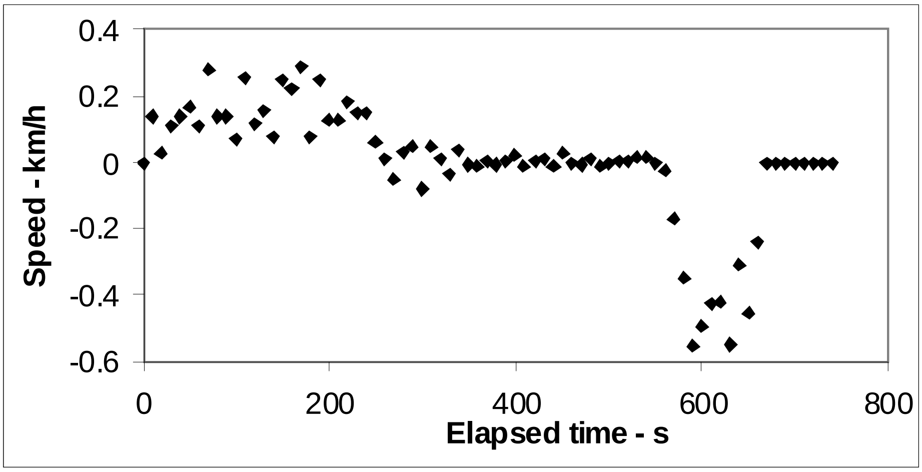


Figure 4.3 Ten-second average accelerations for the operation in Figures 4.1 and 4.2.

Figure 4.3 shows the actual accelerations calculated from the speed time profile. The values are calculated on the basis of 10-second time intervals. There is some scatter of the acceleration and deceleration values, probably due to the differencing technique, which accentuates time and speed error.

The data can also be plotted showing the acceleration as a function of the speed, as shown in Figure 4.4. This is for an entire operation from Copenhagen Central to Ringsted, of which Figures 4.1 and 4.2 represent a single portion between two stations along the route. Each point represents a 10-second average. Here it is a little clearer that the acceleration slowly decreases as the velocity increases, and that the deceleration is nearly independent of speed. The large amount of time spent at the highest speed and constant velocity can be seen by the large concentration of points with very small acceleration and the maximum speed. This diagram is the basis of the model method.

For a given value of speed and acceleration, there is an energy requirement to move the train at that condition. The basic modeling technique is based dividing the operation up into elements characterized by a speed and acceleration range, and then calculating the energy consumption for the average speed and acceleration of the element. If the frequency of occurrence of each element is known, the total energy consumption for an operation can be obtained by the weighted average of the consumption in all the points. The weighting can be made on either a temporal or spatial basis.

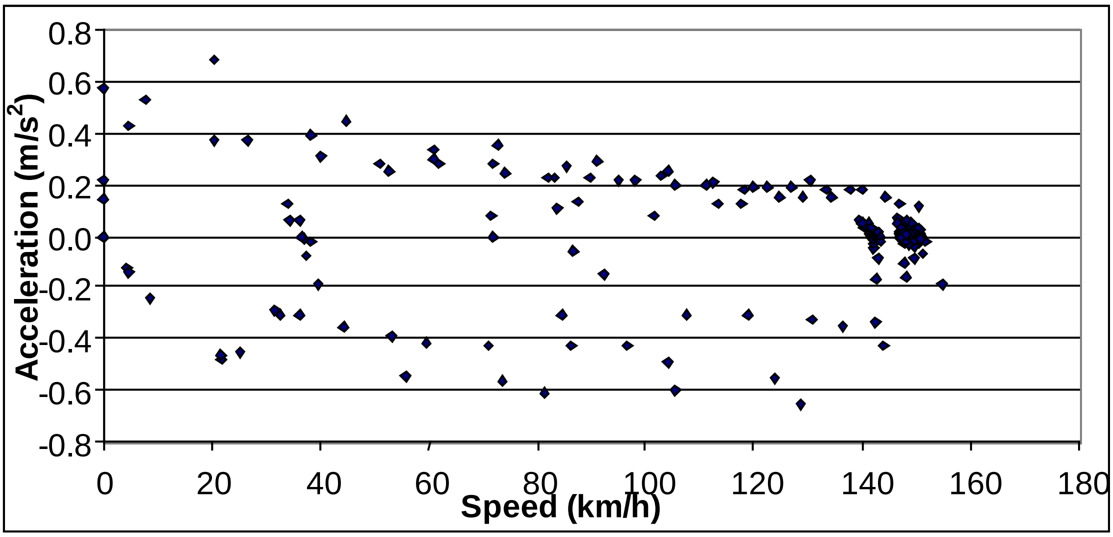


Figure 4.4 Acceleration as a function of speed for the data of Figures 4.1 and 4.2

5 Calculation of Equipment data

In order to calculate the desired results, the overall model needs two forms of input data: Operation data and equipment data. In the following, methods of calculation of the equipment data are described. The equipment parameters of interest are:

- Traction efficiency
- C_R (Rolling resistance coefficient see section 3.1.1)
- C_L (Aerodynamic resistance coefficient see section 3.1.1)

All of these parameters depend on the actual equipment at hand, and can be difficult to calculate exactly without a good knowledge of the equipment. In the model, some reasonable default values will be provided, though the user may change them. Detailed illustrations of the calculation of these parameters are given in an accompanying report (Lindgreen and Sorenson, 2005).

5.1 Traction Efficiency

The efficiencies of different types of trains are discussed in the following. What is of interest is a total efficiency, that is, the efficiency from the electricity lines or from the oil tank. Some of the traction systems used in trains are discussed in the following sections. The trains mentioned are DSB locomotion types, since they were used in evaluating the model. They are typical of a large number of European trains.

5.1.1 Transmission

In locomotives/motor wagons with combustion engines, basically three general types of transmission are used. Each type of transmission has its own characteristics and therefore efficiency.

- Diesel electric
  Here, the mechanical power from the diesel engine's crankshaft is transferred directly to an electric generator. This converts the mechanical power to electric power, which is then transferred to the traction motors at the wheels. The traction motors are connected to the wheel axles through a gearbox. The transmission is designed such that there are limits for how much power can be transferred from the generator to the traction motors. This makes it almost impossible to overload the diesel engine. This also makes it possible to operate the diesel engine in an optimum condition a large portion of the time.

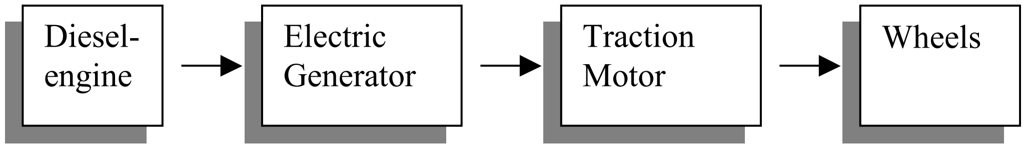


Figure 5.1 Principle of diesel-electric transmission

This construction has the disadvantage of being relatively heavy, but since it is robust, it is often used. In goods trains, locomotive weight is not necessarily a disadvantage, as a heavy locomotive has better traction than a light. This system is used on DSB locomotive types MZ4 and ME.

- Diesel mechanical: The mechanical power here is transferred directly to the wheel axles through a mechanical gearbox. This type of transmission is used on DEB type, on InterCity trains. The system is much like than in a heavy lorry. It has the advantage that there is only a small transmission loss. The efficiency is on the order of 95-98% (DSB).

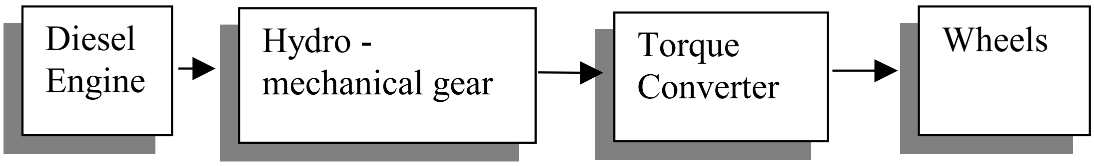


Figure 5.2 Principle in diesel mechanical transmission

- Diesel hydraulic: In this case, a hydraulic gearbox is used to transfer the traction force. Transfer of power from the engine occurs through a pump, which gives an oil pressure, which is transmitted to the gear case at the wheels. This form of transmission has a relatively poor transfer capability, and is found on older versions of trains, for example those used in regional train sets of the type MR by DSB.

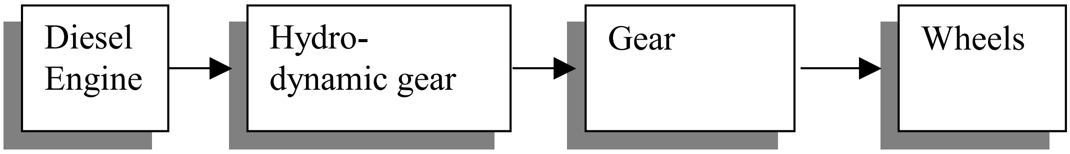


Figure 5.3 Principle of diesel hydraulic transmission

In general, both the mechanical forms of transmission are lighter and less complicated than the diesel electric form. On the other hand, the construction is not as robust, due to a larger number of mechanical parts such as universal joint, drive shafts and gearboxes. It is also easier to overload a diesel engine with these systems than with the diesel electric system.

- Electric: This form of transmission is used on electric trains, and uses a similar principle as the diesel electric locomotive. The difference is that the locomotive receives electricity for the electric traction motors directly from the electricity lines along the track. Electrical equipment on the locomotive adapts the electricity to that type used by the traction motors. The Danish ER- train set is equipped with Asynchronous A/C motors. They have a better output efficiency (about 90%) than older, more conventional electric motors.

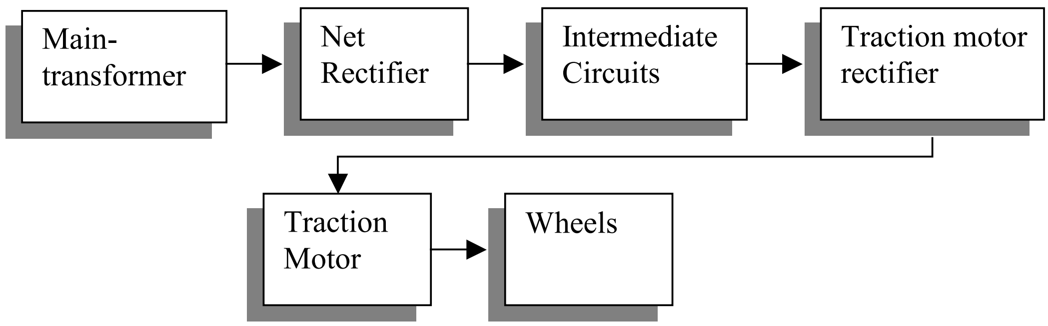


Figure 5.4 Principle of transmission for electric trains

5.1.2 Controller

Control of locomotives and motor wagons is done in a different manner than road vehicles. The following is a short description of the regulation principles for rail locomotion equipment.

MZ4, ME and MR.

The regulation of the engine power is not step less like road vehicles, but occurs through the use of a controller, that in addition to a basic forward and reverse selection function has a controller adjustment with a number of fixed positions. Each of these positions corresponds to a given power for the traction motors. By changing the controller position it is possible to adjust the speed of the train according to signals, gradients or speed limits. The MZ4 and ME have eight controller positions. The type MR train set has only seven controller positions, the last two being stop and idle.

MF and ER.

A given controller position corresponds to a torque at the traction motor/wheel. This is valid, unless limited by the power hyperbola of the engine, that is, as long as the power supplied by the traction motor does not exceed its rating. For both types of train, when the desired speed is achieved, a ”Cruise-Control” system can be activated. This keeps the train running at the desired speed, by using the most appropriate torque. In other words, there is step less regulation in this condition.

5.1.3 Track electrical systems

In general, two different current systems are used in European countries. The most common is an alternating current at a frequency of 16 2/3 Hz.
In a few countries like Denmark and France a more powerful alternating current at 1500 volt 50 Hertz is used. 50 Hz is a frequency that gives a higher power for the traction motors.

5.2 Energy Efficiency

As the above shows, the power system consists of several parts. For diesel power: Diesel engine, transmission and gearing. For electric trains: Main transformer, rectifiers and traction motors. For diesel power, there are different forms of transmission.

5.2.1 Calculation of efficiencies for diesel engines

Regardless of the kind of transmission, the efficiency of the engine itself should be known. In the following, there is a short description of the method of determining the efficiency of the engine.

The engine efficiency is:

$$\eta_e = \frac{P_e}{\dot{m}_f \cdot H_U} = \frac{3{,}6 \cdot 10^6}{b_e \cdot H_U} \qquad (5.1)$$

Where:

η_e is the brake efficiency.
$\dot{m}_f$ is the rate of fuel flow
b_e is the brake specific fuel consumption in g/kWh. (assumed 224 g/kWh)
P_e is the power in kW
H_U is the lower heating value of the diesel oil (assumed 42700 kJ/kg)

The efficiencies for the different diesel locomotives are calculated in the following. The efficiency is calculated for the highest operating step. This means that the efficiency will be a bit higher than for other operating conditions, since the engine usually works best in the high controller steps.

Efficiency for MF

The efficiency of the engine is calculated from Equation 5.1 to be:

$$\dot{m}_f = b_e \cdot P_e \Leftrightarrow \dot{m}_f = \frac{224 g / kWh \cdot 294 kW}{3600 \frac{s}{h} \cdot 1000 \frac{g}{kg}} = 18{,}29 \cdot 10^{-3} kg / s$$

$$\eta_e = \frac{294 kW}{18{,}29 \cdot 10^{-3} kg / s \cdot 42500 kJ / kg} = 0{,}378$$

This type of train is equipped with a diesel-mechanical transmission, which has an efficiency of about 95%. The total efficiency is therefore: 0,36.

Efficiency for MR

The engine efficiency is calculated from the individual operating steps. Only one motor coach is considered, but the efficiency is the same for both. In this case, controller step 7 is used, the highest for this type of train.

$$\eta_e = \frac{237{,}5 kW}{14{,}7 \cdot 10^{-3} kg / s \cdot 42500 kJ / kg} = 0{,}376$$

The MR is equipped with an older version of a diesel-hydraulic transmission. As mentioned in the section of forms of transmission, there is a relatively large loss associated with this type of transmission. For the best conditions, this loss amounts to about 20%, and will otherwise be larger. The average transmission efficiency is assumed to be about 70%.

By using this efficiency, the total efficiency is about 0,26. This value corresponds to similar simulations for two operations between Århus – Hornslet - Århus and Århus – Skjern - Århus (Nielsen, 1983). For these operations, the eifficiencies were found to be 22,7 and 26% respectively. In comparison to the other engines, the efficiency is low. This is partially due to the fact that the engines used here are not turbocharged.

The MR has an efficiency that is more than about 10% lower than the MF.

As mentioned, the values should be taken with some reservation, because of factors such as idling losses and auxiliary power, which can be quite specific for different operations. An average efficiency of 0,24 will be used.

Efficiency for MZ4

For the diesel engine itself, one obtains:

$$\eta_e = \frac{2907kW}{176,5 \cdot 10^{-3}\, kg/s \cdot 42700kJ/kg} = 0,386$$

For the transmission (it is electric) is used:
Generator: 0,9
Traction motor: 0,85
With this, a total efficiency for the entire locomotive is obtained of about 0,3.

Efficiency for ME

For the diesel engine itself, one obtains:

$$\eta_e = \frac{2460kW}{140 \cdot 10^{-3} \cdot 42700kJ/kg} = 0,411$$

The ME has basically the same transmission as the MZ4. But where the MZ4 utilizes conventional direct current, the ME utilizes a more modern alternating current with asynchronous generator and traction motor. It is assumed that the traction motor has the same efficiency as the ER (0,9). For the generator, a higher value of 0,95 is chosen among other things because of its size. With that, a total efficiency of about 0,35 is attained.

5.2.5 Efficiency for electrical locomotive

As opposed to the diesel equipment, the ER does not need to convert chemical energy to electricity and therefore does not have an internal combustion engine. With this, its utilization of the energy it receives is higher. The total efficiency is 0,65. This was determined partially after discussion with DSB and partially on the basis of Swiss values (Frauenfelder, 2000). The values used are for a modern electric locomotive (type Re 466). Consumption values from the study can be seen in Chapter 16. Auxiliary losses are not included directly in the model. This could be accommodated in model calculations be adjusting the electrical locomotive efficiency. A lower value could be used for passenger trains, to account for the needs of climate control, electronics and other passenger facilities not found on goods trains. See Chapter 16 for some indications of values.

The values used are:

Component	Loss	Efficiency
Main transformer	4,2%	95,8%
Net current rectifier	7,5%	92,5%
Intermediate circuit	0,4%	99,6%
Traction motor rectifier	5,7%	94,3%
Traction motor	10%	90%
Auxiliary equipment	7,4%	92,6%
Total	**35,2%**	**64,8%**

Table 5.1 Efficiencies for components of electric locomotives (Frauenfelder, 2000).

This gives a total efficiency of 64,8%, which is rounded to 0,65. This is quite a bit higher than that for diesel powered equipment. In comparison, a train set of the type MF has an efficiency of about 36%. But the efficiency of the electric train is based on the amount of electricity entering the locomotive. One must therefore take in to consideration the efficiency of the electrical energy source.

5.3 Calculation of Driving Resistance

In some cases the resistance values are known ahead of time, and can be used directly. In other cases, especially for goods trains, where the wagon order is not known, to achieve high accuracy, it is necessary to calculate the resistance. The methods are described in detail in the accompanying report (Lindgreen and Sorenson, 2005).

5.3.1 Calculation of C_R

The rolling resistance coefficient is calculated using the method described in (Wende and Gralle, 1997). The method is based on a series of constants that depend on the type of train, as well as the number of axles, speed and weight of the train. Examples of the application of the method and some alternatives are presented in an accompanying report (Lindgreen and Sorenson, 2005). An illustration of the general method is given in the following. Train sets are calculated as locomotives.

The general expression for C_R is:

$$C_R = C_0 + C_1 \cdot \frac{\nu}{\nu_0} + C_2 \cdot \left(\frac{\nu}{\nu_0}\right)^2 \qquad (5.2)$$

Where:

C_R is rolling resistance coefficient
C_0, C_1 and C_2 constants in ‰.
υ is the train speed in m/s.
υ_0 is a constant reference speed of 100 km/h = 27,78 m/s

The constant C_0 can be calculated as:

$$C_0 = \frac{f_{SL} \cdot m_L + f_{SV} \cdot m_w}{m_{train}} \tag{5.3}$$

f_{SL} is the initial value for the locomotive driving resistance (dimensionless)
m_L and m_w are the total weights for the locomotive and wagons respectively.

f_{SV} is calculated to be:

$$f_{SV} = C_{SV} + \frac{F_{at} \cdot n_{AX}}{m_{train} \cdot g} \tag{5.4}$$

Where: C_{SV} is a constant in ‰
F_{at} the axle weight constant of 100 N
n_{AX} is the number of axles
m_{train} is the total weight of the train (m_L+m_V)

Table 5.2 below shows typical values for different types of equipment (Wende and Gralla, 1997):

Equipment type	Constants	Constants
4-Axle locomotive	f_{SL}= 2,5 – 3,5 ‰	
6-Axle locomotive	f_{SL}= 3,5 – 4,5 ‰	
Pass train cars:	C_{SV} = 0,40 ‰	
	C_1 = 0,25 ‰	C_2 = 0,50 ‰
Goods train cars:	C_{SV} = 0,60 ‰	
	C_1 = 0,50 ‰	C_2 = 0,60 ‰

Table 5.2 Typical values rolling resistance constants for different types of equipment.

The results for the calculations of the trains considered are given in Appendix 3. The constants and values used can also be found there. The values from Table 5.2 were used as a starting point.

5.3.2 Calculation of C_L

In other cases, especially goods trains, where the wagon order is usually not known, it may be possible to calculate the aerodynamic resistance from experimental results. The method and programs for this are also described in detail in the accompanying report (Lindgreen and Sorenson, 2005). One can simulate different types of operation, estimate resistance values by adjustment until agreement is obtained. Three types of operation are simulated, coast down, acceleration or constant speed. Of these, the coast down operating is the preferred type, since no data with respect to traction force (controller stage or efficiency) is required. A problem arises if the portion of track where data is available has a significant gradient, which normally is not known. It is necessary to use a significant number of operations to try to compensate for the effects of gradients.

The simulation is performed by using suitable portions of an operating pattern, which are obtained from the train black box/crash log. A portion of operation satisfying the requirements for type of operation must be chosen from the log. The longer the element, in general, the smaller is the error from the calculation. In addition to the speed time/distance data, material data like weight, frontal area, and gradient (if available) are needed.

For the train sets, values from DSB were used along with measurements from WS-Atkins. The calculations of these can be seen in Appendix 4.

The values used for C_L, and the constants for the calculation of C_R for the equipment used, with the exception of the train sets, are shown in Table 5.3.

	MZ4	**ME**	**Bn/ABns**	**B7 (svensk)**	**Habbinss-y**
C_L	1,1	1,1	0,11	0,11	0,15
f_{SL}	0,004	0,004	-	-	-

Table 5.3 Constants for the calculation of rolling resistance.

The values for C_L are per unit.

6 Model Principle

6.1 General

It can often be quite complicated to obtain and process detailed driving patterns. It is often difficult to obtain a driving pattern for precisely that type of operation or runs that are desired to be simulated. It can also be complicated to process and calculate, since detailed data for such a driving pattern can quickly become very extensive. At the same time, there is a limitation as to what can be simulated. Normally it is possible to use detailed simulation models, from which with the use of detailed route and equipment data it is possible to simulate operation for a given stretch of railway.

The purpose of the method developed here is to offer an alternative to the detailed second-by-second calculation model, which operates in a simpler and more transparent method. The method should give more flexibility in connection with the application of the model to a variety of needs.

In place of the use of a complete driving pattern with detailed sequential measurements of time, speed and/or distance, attention is focused on the calculation of energy consumption in a more general way. As described in the section of driving resistance, the energy consumption is equal to the product of the driving resistance multiplied by the driven distance. For a given train, the parameters used to calculate steady state driving resistance are at most a function of speed. The force used to obtain acceleration is directly proportional to this acceleration. Thus by specifying the speed and acceleration, all the forces involved in train movement on a level line can be obtained. To be completely accurate, gradient resistance should be included too. However, detailed gradient information for rail lines is most difficult to obtain. Therefore, the model will be based on the assumption of flat operation. Since it is more likely that elevation differences between cities can be found. Gradient corrections will be added for an over all trip, with which it is assumed that only the net elevation difference affects the energy consumption of a route. Up and down operation are assumed to be equivalent with opposite signs, thereby canceling each other.

Using the matrix approach, then operation is divided into a collection of elements, each having a maximum and minimum velocity and acceleration. For the determination of the driving resistance and energy consumption, the average value of each is used for the calculation of any operation point that lies within the limits of the element. Since both acceleration and gradient resistance are proportional to the train mass gradient resistances could be included in calculations by a correction to either rolling resistance or acceleration resistance. Therefore, it is apparent that speed and acceleration are good choices for the fundamental parameters in a simplified model.

Duration operation between two locations, an ideal operation consists of a number of accelerations, operations at constant speed, and then brakings. This pattern will be similar between every stop. By constructing a distribution of how often different driving conditions (speed, acceleration) occur, in principle it is possible to simulate an arbitrary driving pattern. Such a model includes the assumption that all operation modes are independent of each other. Under this assumption, the model can be used for any sized network, from an individual train route to a large network. For different types of trains, the physical parameters must be changed. Since the physical parameters of the train are directly accessible, this is readily accomplished.

The principle used then is a matrix of operating conditions described by speed and acceleration. This principle has been used in the simulation of on-road heavy-duty vehicle operation. By dividing the driving pattern into speed intervals and then further dividing these into accelerations it is possible to describe the operation of the train. Each matrix element has its speed interval and acceleration interval. By the use of an average speed and acceleration for each interval, and the driving resistance of the train, it is possible to estimate the energy consumption of the train for that matrix element. For an entire driving pattern, the total energy consumption can be estimated buy using a distribution matrix for the elements, that is a distribution of driving conditions, and then summing the weighted energy consumption of the entire operation.

Ideally, the emissions are a function of each operating condition, that is, they can vary between the operating elements. But in this work, emissions will be calculated from the integrated energy consumption, since reliable data concerning actual emissions for the individual modes in not available. This is only relevant in the case of diesel train emissions, since electricity generation is from entirely different kinds of sources, where there is no connection to the actual operation of the train. The principle of the model is shown in Figure 6.1.

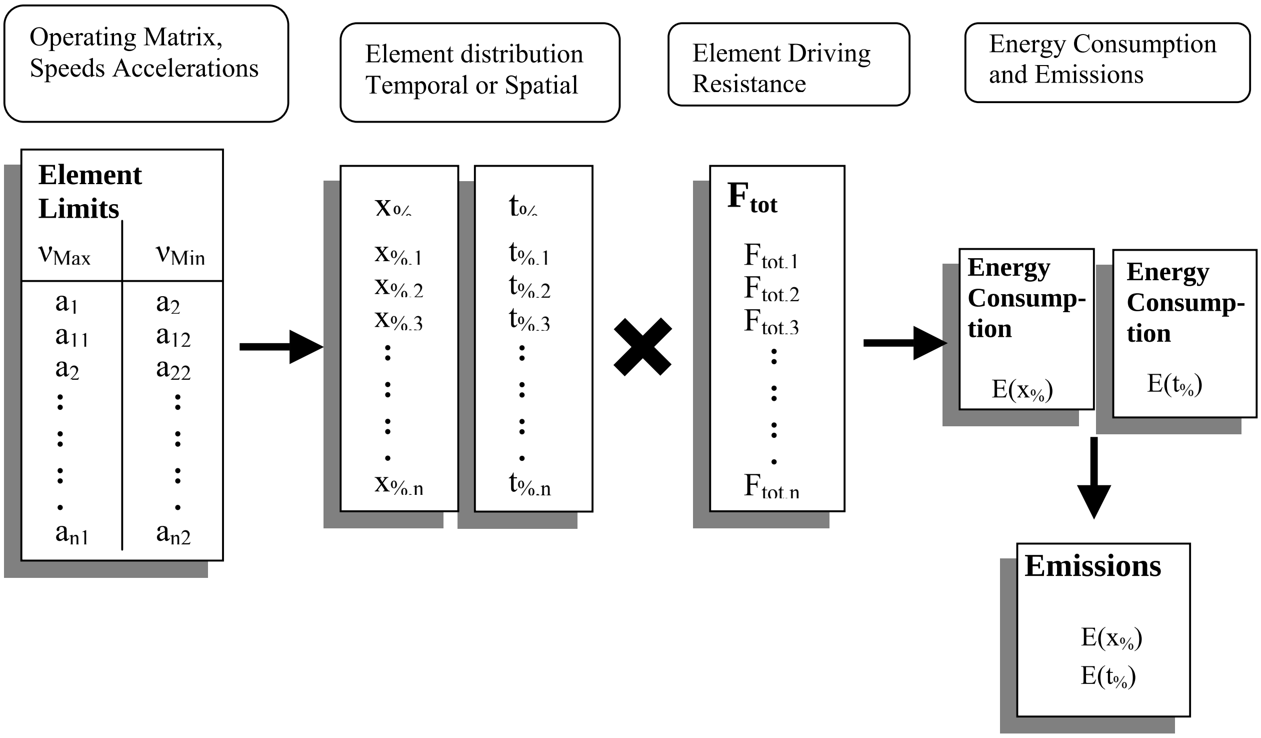


Figure 6.1 Overall structure of the calculation model.

Figure 6.1 shows that the driving pattern can be characterized on the basis of either driving time or distance. The latter may prove to be more useful for conditions where the geographical features of a railway net are available.

The model then is not based on a detailed driving pattern, but on a general distribution of the types of operational modes - speeds and accelerations. It can then be called a model on the macro-level, where the calculation of the detailed driving pattern must be done on the micro-level, i.e., second-by-second or meter-by-meter. The size in the intervals in the distribution matrix is of course important to the accuracy of the method. This issue will be addressed in subsequent sections on testing and evaluating the model.

As earlier mentioned, a driving pattern is typically a description of the velocity as either a function of elapsed time or driven distance. The two are equivalent, and a speed time history can easily be integrated to obtain a distance time history. However, it is expected that the users of this model will not be interested in detailed driving cycles, but rather in a position to analyze rail operations on a larger scale. In this case, it is of interest to evaluate rail operations in terms of a temporal or spatial distribution of the chosen speed acceleration elements. It should be possible to obtain representative values for different types of operation. This will also be addressed in subsequent sections. Data availability or type application will determine which form, temporal or spatial, is most useful. Both forms will be investigated in this report.

6.2 The Model in Practice

After discussing the reasons behind the nature of the driving profiles, it is possible to use them to attain the final goal: Modeling of the driving pattern and analysis of the temporal and spatial distributions of the driving patterns. The purpose is initially to illustrate the distribution of speeds and accelerations for a driving operation.

As mentioned earlier, a driving pattern can be written in terms of either the elapsed time or the driven distance. By using time as the parameter, one can see how much of the time a train spends in a given operational mode (speed - acceleration). Correspondingly, by using a spatial distribution, one obtains a knowledge of which percentages of the driven kilometers are driven within a given operational mode.

It may be interest to show how large a portion of the operating time is used for the different driving modes, for example acceleration, or how much of the traveled distance is driven at constant speed. The results from using these two different bases will not appear the same. This is because the equations of motion expressed with x and t respectively are not identical. According to equation 4.1 for constant acceleration, v(t) is given by a second order equation, while v(x) is linear. In addition, a stopped train will indicate only one point in a spatial distribution, regardless of the time spent stopped. This will have an influence on the appearance of the distribution. In principle, a spatial distribution by itself cannot calculate the emissions from a train when stopped. In general, energy consumption is low when a train is stopped and the error is not large, especially considering other uncertainties. This will be shown later. Corrections can be made using an estimate of average stop time in the case of passenger trains. Freight trains are more difficult to describe in this respect.

As an illustration, Figure 6.2 shows a speed-distance diagram for operation of the Danish IC3 (MF) between Copenhagen main station and the town of Ringsted.

The operation consists of 3 similar patterns of different lengths, which depend on the distance between stations. When the train has been stopped and then starts, it accelerates up to the desired speed, which is 140 km/h. When this speed has been achieved, it operates with constant speed until the next station is approached and deceleration begins. It is this repetitive nature of operation that makes the element matrix method appealing.

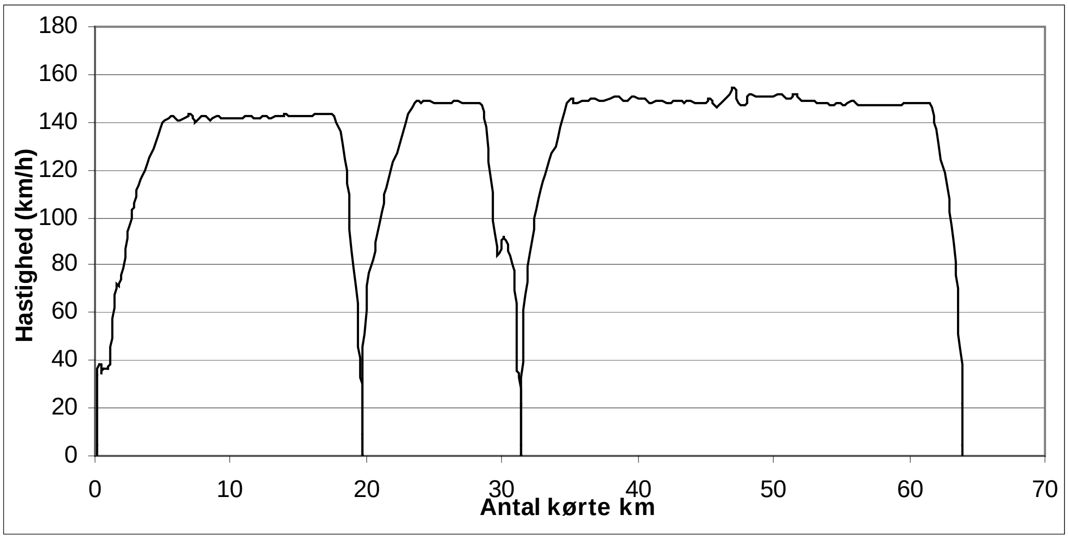


Figure 6.2. Driving Pattern for the Danish IC3 train between Copenhagen and

A more detailed presentation of the driving pattern can be seen in Figure 6.3. This is the same data as Figure 6.2, presented on speed acceleration co-ordinates with each point corresponding to average values over a ten-second interval.

The grid lines in the figure give an example of how one might select acceleration and speed intervals for further analysis. Not all elements are relevant for this pattern, as there are some conditions where the train does not operate. It is also characteristic for a train, as for all wheeled vehicles, that as the velocity increases, the maximum acceleration decreases.

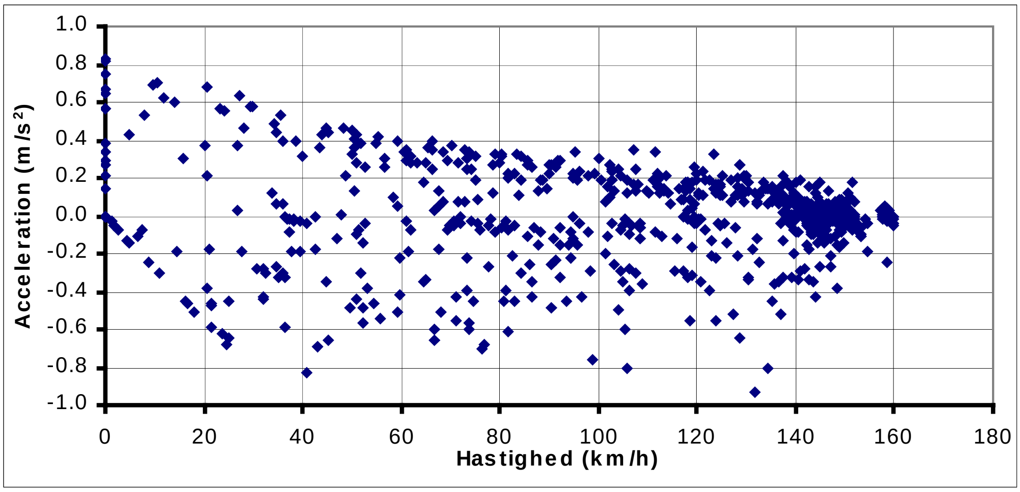


Figure 6.3. Operation pattern in speed and acceleration for MF Copenhagen-Ringsted.

Figures 6.2 and 6.3 have been constructed from a measured driving pattern, with an interval of 10 seconds. That means that each point on the figure can be considered to be a 10-second average value.

There are 90 elements in the matrix of Figure 6.3, 10 acceleration intervals and 9 speed intervals. These have been chosen for the purpose of illustration here. On the acceleration portion, it is clear the several of the elements are never encountered in operation. It is likely that this is due to power/torque limitations of the equipment, although this cannot be stated definitely without a technical analysis of the train.

Figure 6.4 shows an individual element. In this case the max/min values for the acceleration are 0.4 and 0.2 m/s^2 for the speed 60 and 40 km/h. The figure shows that three of the 10 second operating points fall within the criteria of the element.

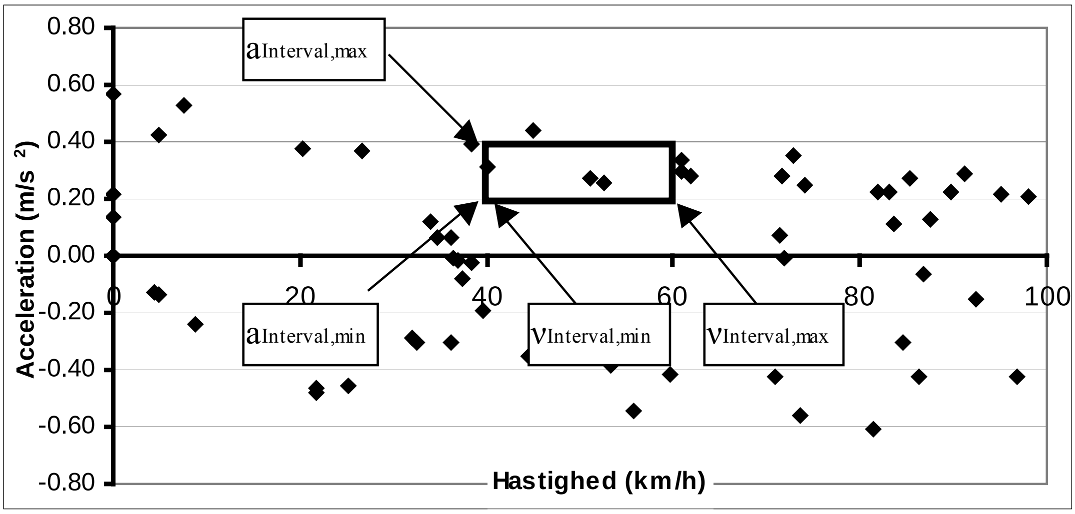


Figure 6.4 Schematic figure of the element in the acceleration speed matrix.

Since the purpose of the model is to calculate energy consumption and emissions, the lower portion of the pattern in Figure 6.4 is not taken into consideration (that portion including deceleration). This is satisfactory for this type of train, since there is no regenerative braking. There is always an amount of emission and fuel consumption for stop/idle conditions. However, in relation to the consumption in the powered modes (acceleration and constant speed), it is quite small. Appendix 2 gives an analysis of the load collective for a goods train and a passenger train, and supports this observation.

Then for this train, it should be adequate only to calculate energy consumption and emissions for conditions with acceleration greater than or equal to 0. In the case of regenerative braking, the negative acceleration portion is relevant, since it determines the amount of energy available to be put back into the electric lines. This simulation is more difficult than the energy consumption, since regenerative braking could be considered "optional", whereas the energy to move the train with positive acceleration must be supplied for any kind of train.

6.3 Analysis of a driving pattern

The distribution of operating points could be made on the basis of either absolute values or in terms of percent, the latter being the simplest and most general. It will be utilized here. When the distribution has been completed, the calculation of the energy consumption for each relevant element case can be performed. This is done using the physical properties of the train and a representative speed and acceleration for the given block, normally the average value for the element. As mentioned previously, it is theoretically possible to determine emissions for each element, but due to lack of data, emissions calculations will be based on average energy consumption over a complete driving pattern.

Each operating point must be evaluated according to the criteria chosen for the size of the matrix elements. These can be written as:

If

$$v_{interval,\min} \le v_{\log} \le v_{\text{Interval,max}} \text{ where: } v_{\log} = \frac{v_1 + v_2}{2} \qquad (6.1)$$

and if:

$$a_{interval,\min} \le a_{\log} \le a_{\text{Interval,max}} \text{ where: } a_{\log} = \frac{v_2 - v_1}{t_2 - t_1} \qquad (6.2)$$

Then the percent value for t is:

$$t_{\%} = \frac{t_{interval}}{t_{acc} + t_{a=0} + t_{v=0}} \text{ and } x_{\%} = \frac{x_{interval}}{x_{acc} + x_{a=0} + x_{v=0}} \qquad (6.3)$$

Where:

$v_{Interval,max}$ and $v_{Interval,min}$ are the limits for the given speed interval.
$a_{Interval,max}$ and $a_{Interval,min}$ are the limits for the given acceleration interval.
v_{log} and a_{log} are the speed and acceleration from the logged driving pattern.
v_1 and v_2 are the initial and final speed for the given measurement period.
a_1 and a_2 are the initial and final acceleration for given measurement period.
$t_{interval}$ and $x_{interval}$ are the time or distance spent or driven in the element.
t_{acc}, $t_{a=0}$ and $t_{v=0}$ are the total time of acceleration, constant speed and stop.

x_{acc}, $x_{a=0}$ and $x_{v=0}$ are the total distance of accel, constant speed and stop. $x_{v=0}$ is naturally = 0.

That is to say again, that the energy consumption in the case of deceleration is assumed to be negligible.

The energy consumption can now be calculated as:
For the spatial distribution:

$$E(x_{\%})_{,net} = \frac{\sum F_{tot} \cdot (x_{acc} + x_{a=0} + x_{v=0})}{\sum x_{\%}} \qquad (6.4)$$

Where:

$E(x_{\%})_{,net}$ is the total energy consumption ”at the coupler” – that is, the energy that must be supplied to the wheels.
ΣF_{tot} is the total driving resistance in the element
x_{acc}, $x_{a=0}$ og $x_{v=0}$ are the total distances traveled under acceleration, constant speed and stopped.
$\Sigma x_{\%}$ is the percent of the distance the train covers in for the conditions of the element.

Correspondingly for the temporal distribution:

$$E(t_{\%})_{,net} = \frac{\sum F_{tot} \cdot x_{tot} \cdot (t_{acc} + t_{a=0} + t_{v=0})}{t_{tot} \cdot \sum t_{\%}} \qquad (6.5)$$

Where:

$E(t_{\%})_{,net}$ is the total energy consumption ”at the coupler” – that is, the energy that must be supplied to the wheels.
ΣF_{tot} is the total driving resistance in the element
x_{tot} is the length of the driven stretch
t_{tot} is the total driving time
t_{acc}, $t_{a=0}$ og $t_{v=0}$ are the total times for acceleration, constant speed and stopping.
$\Sigma t_{\%}$ is the percent of the total driving time, during which the driving pattern is in the given element.

6.4 Operation with constant speed.

When dividing the operation intervals a problem can arise. That is, how does one in practice define operation where the speed is constant? As seen from the figure about

(Figure 6.4) the operation contains several stops. Every time the train has stopped, it must again be accelerated up to the desired speed. When this is achieved, the speed is held at this level until the next stop occurs, at which time the braking starts.
The speed is not completely constant, but in practice varies in the range of 1 - 3 km/h. When the speed changes, strictly speaking this will either be acceleration or a deceleration - even though in general this condition is regarded as constant speed operation.

Some assumptions

In addition to the problem of defining constant speed operation, there are other uncertainties in the method. This applies to conditions such as:

- All operation with negative acceleration was omitted from the calculation. The model is applied to only about 50 to 70% of the total driving pattern. This applies to either the spatial or temporal distribution. It also means that losses at idle and consumption during deceleration are omitted.
- The efficiency for traction is based on an average value. Efficiency varies according to which operating condition the train is in. The highest efficiency will typically occur in the highest loading levels, though not necessarily the highest.
- Local gradients are not included. Gradient values used are based only on the height difference between the origin and destination. It is assumed that there is 100% recovery of potential energy.
- Tunnel operating is neglected. Several of the simulations to follow involve some operation in the tunnel under the Great Belt, where there an additional air resistance could be expected (tunnel factor).
- The driving resistances included are the rolling resistance, F_R, The aerodynamic resistance, F_L, the acceleration resistance, F_A and the gradient resistance F_S. Other driving resistances are omitted. Among these can be named; Curve resistance, brake disc resistance, and air impulse resistance. Curve resistance is briefly described in the section on driving resistance. The other resistances are described in Lindgreen and Sorenson, 2005. These resistances are normally of minor significance and are therefore not included.

A flow diagram for model calculations is shown in Figure 6.5. A more detailed of the model program, its structure, inputs and outputs in included in the users manual, (Cordiero, Lindgreen and Sorenson, 2005).

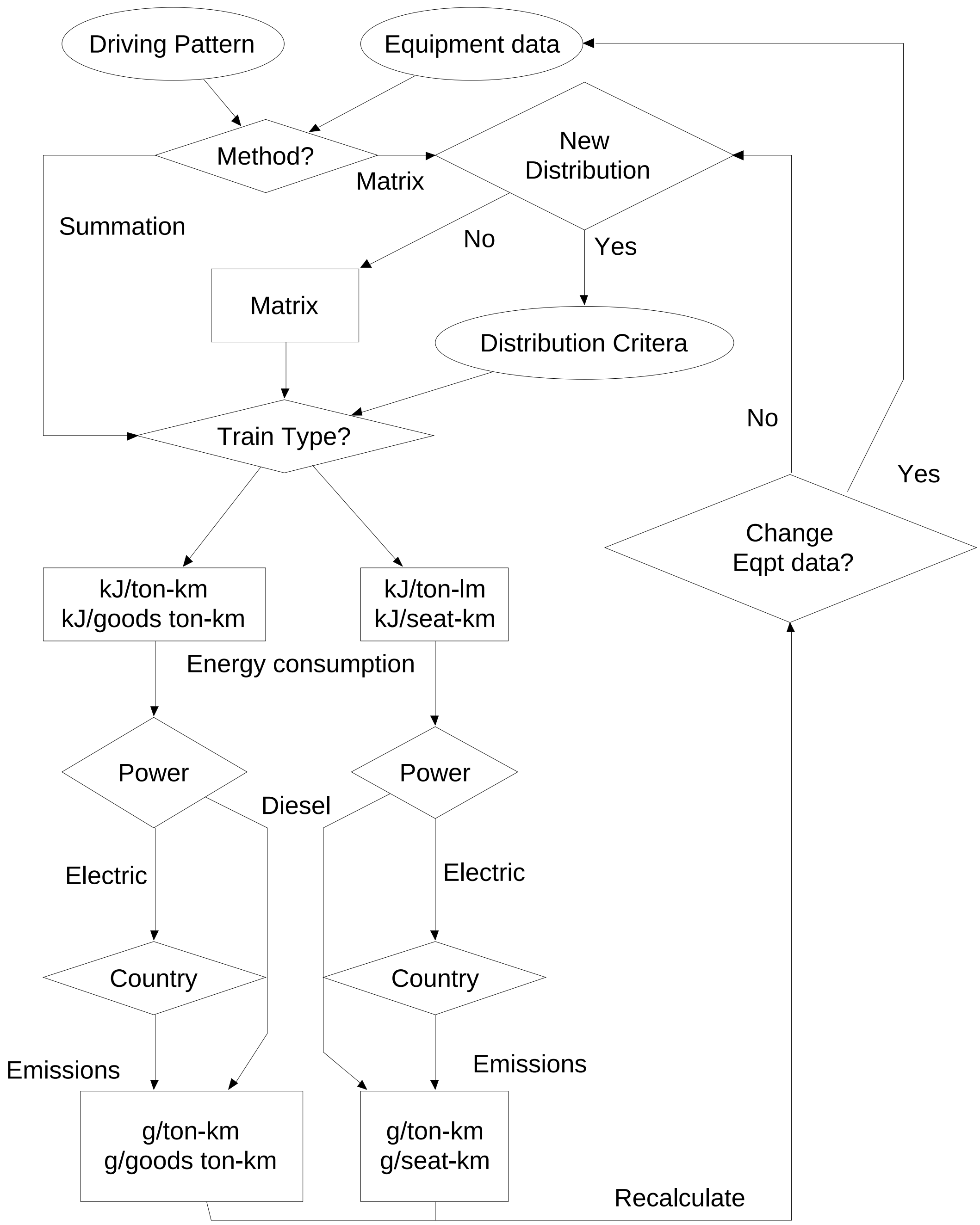


Figure 6.5 Flow diagram for the model

7 Model

The overall goal of the project is to be able to calculate driving resistance, energy consumption and emissions for an arbitrary operation. This can be done from different points of view. The intention is to be able to calculate energy consumption from as simple prerequisites as possible.

The model is constructed in MS Excel®. This involves advantages and disadvantages. This platform was chosen due to a general desire to make the model simple to use. At the same time, it should also give a large degree of availability and transparency, since the programming is straightforward. In order to make the model more user-friendly, stabile and clear, the user interface contains some of the data to be processed as well as the results of the processing. All calculations are conducted with macros, that is, programs written in the language Visual Basic Applications (VBA).

The model was built to calculate on the basis of an operation matrix entered by the user, and from that determine energy consumption and emissions.

The model is constructed on the principle of operation distributions for velocity-acceleration elements, using the previously described technical basis.

7.1 Cycle Analysis

A procedure was developed to perform calculations from the detailed description of the operation of the train. Two calculations were performed. The first is the calculation of the energy consumption from the detailed train movement. That is, for each measured point of the driving pattern, the driving resistance was calculated. This was summed up over the entire pattern, and used to compare with the results of the analysis of the same cycle by the matrix approach. These comparisons will be shown later. It is required that the driving pattern includes values for the location (distance) time, and speed, in that order.

The second was to analyze the statistical aspects of the operation. That is, at the amount of time or distance spent in the different driving modes was determined for use in a statistical description of the driving cycle to be used in the matrix approach for analyzing the cycle and to determine typical statistical descriptions of the operation of the various types of trains analyzed.

A series of sheets and macros were programmed in MS Excel® to perform this analysis. The following describes the structure of the individual sheets, their function and connection with the other sheets. Only the sheets that are accessed under use and therefore are visible are discussed. Figure 7.1 shows a sketch of the structure and the connection between the sheets.

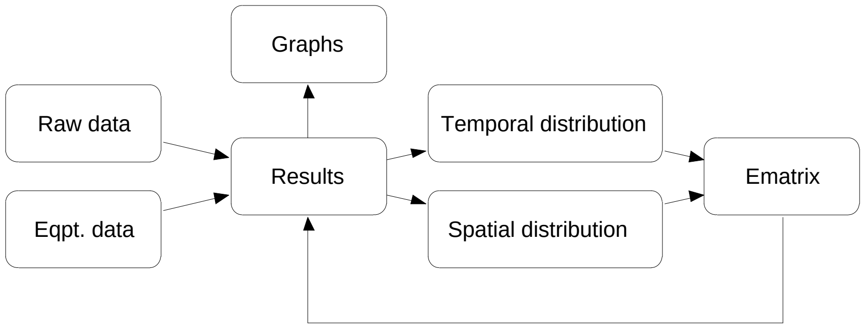


Figure 7.1 Structure of cycle analysis model.

Raw data: The driving pattern is read here. The data entered are the distance traveled, the elapsed time and the speed. The data for the equipment, environment etc. can also be entered here.

Results:

The results calculated were the overall characteristics for the driving pattern. That is, driving time, traveled distance, minimum, maximum and average values for time, speed and acceleration. Also calculated were the portions of the various types of operation are calculated as on both the basis of time and distance. That is, how much time does the train use for different types of operation, as well as how much of the total distance is used for these types of operation. The four types of operation are acceleration, constant speed operation, deceleration and stop. Values are calculated on both an absolute and relative basis.

Distribution Sheet: The distributions of operating conditions are written in two distribution sheets. One is for the temporal distribution and the other is for the spatial distribution. The two distributions are calculated on the basis of the chosen speed and acceleration intervals. The effects of interval size will be shown later. The calculations take place by summing the time and distance values for all acceleration interval at a given speed interval.

The distribution is expressed in both absolute and relative (%) values. For each speed interval, the accompanying acceleration intervals and their respective values are listed.

E-matrix: The matrix describing the frequency of the operating conditions is called the E-matrix. It was calculated for individual driving cycles to compare with the point-by-point calculation, and to collect statistical information for the determination of typical E-Matrices for the different types of trains. The energy consumption based on the both the spatial, E(x%) and temporal, E(t%) distributions was calculated for comparison purposes.

Graphs: This sheet is only an output sheet where the driving pattern can be illustrated in several forms. To start with are found the conventional ν/x and ν/t-diagrams. Then there is the illustration of acceleration as a function of speed (a/ν-diagram) and acceleration as a function of its length (acceleration lengths). In addition, pie charts are drawn for the distribution of the type of operation. These are drawn in % of the total time or distance traveled.

7.2 Energy Consumption and Emissions Model

Based on the procedures described previously, a comprehensive model was developed for the calculation of emissions and energy consumption for rail transport. The structure of the model and instructions on how to run it, and modify the data and other important portions of the model are described in the users manual for the model (Cordiero, Lindgreen and Sorenson, 2005). Some of the more important features are mentioned here. The model allows changes in operating parameters of trains. An accompanying report discussed technical factors determining the driving resistance of a variety of train types (Lindgreen and Sorenson, 2005).

The model contains E-matrices for the following types of trains, Goods, Urban Passenger, Regional passenger, Inter-City passenger and High-speed. They are stored in separate locations in the spreadsheet, and read for operation with the appropriate train types. It is possible for the user to change the data, and separate matrices are established for each country.

The structure of the model makes is possible to calculate individual trains, or to calculate the trains from a given country. When written, the model contains rail network and traffic information consistent with the TRENDS study (Georgakaki, *et. al.*, 2002). The model is programmed to read data after country codes, and the user may readily modify existing network and traffic data, or establish new route, countries or even individual trains. Traffic data is entered on a time series basis.

8 Test of model

The principles of the model were tested to investigate the quality and to compare with more detailed procedures. Since there are many simplifications and approximations in the model, it cannot be expected that the results will be precise. But it is of interest to investigate the overall accuracy of the calculation procedure and the general trends.

In the comparison, there are three different calculation methods for the energy consumption. The first is calculated on the basis of the temporal distribution of the operating conditions using the matrix approach. The second is based on the spatial distribution of the operating conditions, also using the matrix approach. The third procedure is the "conventional method", where based on the instantaneous condition of the train, its energy consumption is determined and then summed over the entire driven stretch. The last value is a reference value, since it uses the same physical parameters as the operational matrix. The comparison between this value and that based on the distribution matrix concept shows the errors introduced by breaking the operation into driving elements, and using the spatially or temporally weighted sum.

In this regard, then it is E(x%) and E(t%), that are to be evaluated. In addition, data was obtained from the Danish National Railway (DSB) for the detailed operation of the trains. For diesel-powered trains, it was possible to determine the energy consumption based on the logged values of the controller stage for the locomotive, and a knowledge of the energy consumption of the diesel engine in each controller stage.

8.1 Test

The model was tested by calculating different experimentally measured operating patterns. The results were compared with corresponding measurements from the DSB. These runs were specially chosen for availability of data on the arrangement of the train and a loading collective for determining power consumption. The trains used in the comparison were diesel trains, but the basic energy consumption for an actual train is basically the same for electrical and diesel engines. The only difference being in the efficiency of the drive systems. In these cases, both the energy consumption and emissions have been calculated from DSB data, based on available engine emissions measurements. This gives an experimentally correct basis for comparison of model predictions.

The energy consumption is straightforward to calculate. The same applies to CO_2 og SO_2, emissions, since these are directly related to fuel consumption in a diesel powered train. The other emissions NO_x, CO, HC and particles (PM) are more dependent on the specific material. In the model, average emissions factors are utilized, which are not

equipment dependent, although this can in principle easily be changed in the calculations.
To give the most useful results, the choice of run was made from these criteria:

- The energy consumption and emissions were calculated by DSB.
  The arrangement of the train, that is, number of wagons, total weight, number of seats/goods-tons and wagon weights were known.
- Driving resistance values known or calculable without risk for major error.
- Emphasis was placed on the knowledge of C_L, since C_R be calculated fairly accurately, if the conditions of the arrangement of the train are satisfied. C_L can be calculated for equipment specifications. Coast down tests were only used on the two goods trains.

Since the calculations from DSB were based on knowledge of equipment, this gives a good basis for comparison.

In total, 25 runs were analyzed.

Passenger train
Three types of train were tested: Regional train RØ (Regional East) and RV (Regional West) as well as two express trains (InterNord):

- Regional train with ME power (2)
- Regional trains with MZ4 power (4)
- Express train with MZ4 power (2)
- Regional train with MR power (10)

For all MR operations, one train set was used.
The resistance values for the MR are calculated in (Lindgreen and Sorenson, 2005) For the locomotive powered trains, C_L for locomotives is 1,1 and for the passenger wagons 0.11. C_L can then be expressed in the following equation as a function of the number of wagons:

$$C_L = 1{,}1 + n_{wagons} \cdot 0{,}11 \quad (8.1)$$

Goods trains
Two types of trains were examined here: a mail train and a normal goods train:

- Goods train with MZ4 power (2)
- Goods trains with ME power (1)
- Post train with ME power (9)

Since several of these change the number of cars underway in reality there are 11 operating conditions.

The general procedure in the data processing is, that every time a train (usually goods train) changes arrangement, the following operation is calculated as a separate operation from the previous.
The goods trains tested have the advantage that they are frequently post trains. That is, the trains consist of uniform wagons of a known type, which means that the trains are homogeneous. Therefore, C_L and C_R are relatively simple to calculate. Simulation of coast-down or steady operation is not needed to calculate C_L. There are goods wagons with four axles and nearly uniform profile (the type of car is seen in Appendix 1). C_L for these cars is about 0,15, and for the locomotive, in all cases is an ME, $C_L = 1,1$. C_L can therefore be expressed in the following equation as a function of the number of wagons:

$$C_L = 1{,}1 + n_{wagons} \cdot 0{,}15 \qquad (8.2)$$

In addition to the post trains, there are also three normal goods trains. For there, C_L is calculated from simulation of coast-down. C_R is calculated in the normal way, since all the data for the weight of goods and tare weight are known.

A summary of the conditions for all the goods trains is shown in Table 8.1 and for all passenger trains, the conditions are shown in Table 8.2.

Table 8.1 Summary of all goods trains used. All weights are in tons. A list of the station abbreviations is found in Appendix 5.

Dato	Tognr.	Fra	Til	Km	Lokomotiv	Antal vogne	Godsvægt	Belastningsvægt	Tara, vogne	Tara, lok	Total vægt	Længde	C_L	C_R
27/1 99	GP7291	Rg	Od	95.8	Me1535	12	160	457	297	115	572	310	2.90	2.97E-03
25/1 98	GP7501	Gl	Od	148.7	Me1535	6	0	314	314	115	429	190	2.00	3.05E-03
7/5 99	GP7502	Fa	Sg	156	Me1510	10	180	448	268	115	563	260	2.60	2.90E-03
7/5 99	GP7502	Sg	Gl	56.5	Me1510	7	180	448	185.5	115	480.5	190	2.60	2.17E-03
10/5 99	GP7502	Fa	Od	60	Me1505	10	180	448	268	115	563	260	2.60	2.85E-03
3/2 99	GP7506	Od	Gl	148.5	Me1521	4	72	291	219	115	406	120	1.70	3.19E-03
4/5 99	GP7523	Gl	Fa	211	Me1505	7	126	314	188	115	429	190	2.15	3.14E-03
4/5 99	GP7523	Fa	Ar	108	Me1505	6	126	314	188	115	429	160	2.00	3.02E-03
4/5 99	GP7523	Ar	Tov	9.5	Me1505	3	126	314	188	115	429	100	1.55	2.28E-03
26/1 99	GP7516	Tov	Fa	115	Me1535	2	36	90	54	115	205	70	1.40	4.09E-03
26/1 99	GP7516	Fa	Gl	211	Me1535	8	144	358	214	115	473	210	2.30	3.07E-03
25/1 99	G9409	Gb	Kj	52.5	Me1508	25	1358	2043	685	115	2158	520	7.50	1.58E-03
24/3 99	G9521	GB	Kb	108	Mz4 1458	8	0	229	229	123	352	150	4.70	3.07E-03
26/3 99	G9521	GB	Kb	108	Mz4 1458	11	130	416	286	123	539	170	4.70	2.68E-03

Table 8.2 Summary of all passenger trains used. All weights are in tons. A list of the station abbreviations is found in Appendix 5.

Dato	Tognr	Fra	Til	Km	Lokomotiv	Antal vogne	Tara,vogne	Tara,lok	Total taravægt	Passagerer	Længde	Start tid	Slut tid	C_L	C_R
24/2 99	IN392	Kh	Hg	45.7	MZ 1457	7	308	123	431	520	220	22:05	22:40	1.870	2.39E-03
25/2 99	IN 392	Kh	Hg	45.8	MZ 1457	11	484	123	607	840	280	22:05	22:40	2.310	2.17E-03
26/3 99	Rø3061	Hg	Kh	46.0	Mz1458	6	217.5	123	340.5	440	170	16.09	16.57	1.76	2.83E-03
25/3 99	Rø4557	Kk	Kb	113.8	MZ 1458	8	289.5	123	412.5	600	220	15.32	17.15	1.98	2.46E-03
24/1 99	RØ4287	Kk	Næ	90.5	ME 1514	4	145.5	115	260.5	280	120	22:54	24:05	1.540	2.96E-03
25/1 99	RØ4219	Kk	Nf	148.1	ME 1514	4	145.5	115	260.5	280	120	6:51	8:47	1.540	2.96E-03
23/3 99	Rø2269	Kk	Nf	149.6	Mz1458	6	217.5	123	340.5	440	170	18.54	20.55	1.76	2.57E-03
31/3 99	RØ1529	Kh	Kb	110.2	MZ 1458	5	181.5	123	304.5	360	150	08.40	10.15	1.65	2.80E-03
28/6 99	3506	Gr	Ar	69.0	MR 4044	1 sæt	-	-	69	132	44.68	5:00	6:23	0.967	1.83E-03
24/6 99	3521	Ar	Al	140.4	MR 4041	1 sæt	-	-	69	132	44.68	17:44	18:23	0.967	1.83E-03
24/6 99	3856	Ti	Ar	278.4	MR 4041	1 sæt	-	-	69	132	44.68	12:59	15:45	0.967	1.83E-03
24/6 99	3521	Ar	Al	140.4	MR 4041	1 sæt	-	-	69	132	44.68	17:44	18:23	0.967	1.83E-03
25/6 99	5293	Al	Fh	84.9	MR 4041	1 sæt	-	-	69	132	44.68	4:56	6:27	0.967	1.83E-03
25/6 99	5226	Fh	Al	85.0	MR 4041	1 sæt	-	-	69	132	44.68	6:52	8:10	0.967	1.83E-03
23/6 99	5249	Al	Fh	84.7	MR 4090	1 sæt	-	-	69	132	44.68	18:46	19:55	0.967	1.83E-03
24/6 99	5209	Ab	Fh	84.7	MR 4090	1 sæt	-	-	69	132	44.68	8:46	9:55	0.967	1.83E-03
24/6 99	5252	Fh	Ab	84.7	MR 4090	1 sæt	-	-	69	132	44.68	14:17	15:24	0.967	1.83E-03
24/6 99	5268	Fh	Ab	84.1	MR 4090	1 sæt	-	-	69	132	44.68	17:21	18:29	0.967	1.83E-03
23/6 99	3917	Ar	Hr	93.8	MR 4090	1 sæt	-	-	69	132	44.68	7:52	9:22	0.967	1.83E-03

8.2 Comparison of results

The calculated consumption from the model was compared to the corresponding data from DSB. The latter were calculated from the load collectives. That is they were based on fuel consumption and engine emissions data.

For passenger trains, the consumption is in kJ per seat km and the emissions in g/seat km. For the goods trains the consumption is in kJ/ton km. For clarity, the results are shown graphically. The main comparisons shown here are fuel consumption and emissions of CO_2 and NO_x. DSB values are called reference values and they are compared to the calculations based on the spatial and temporal distributions $E(x_{\%})$, $E(t_{\%})$. Also shown is a calculation based on the integration of a detailed model at every data point (change in conditions). Results for HC, CO and particulate emissions are shown in Appendix 7.

Energy Consumption

For the passenger trains, the consumption is divided into the locomotive powered trains (ME/MZ4) and the train set MR.

Figure 8.1 shows energy consumption per seat km for operation with the MR-train set.

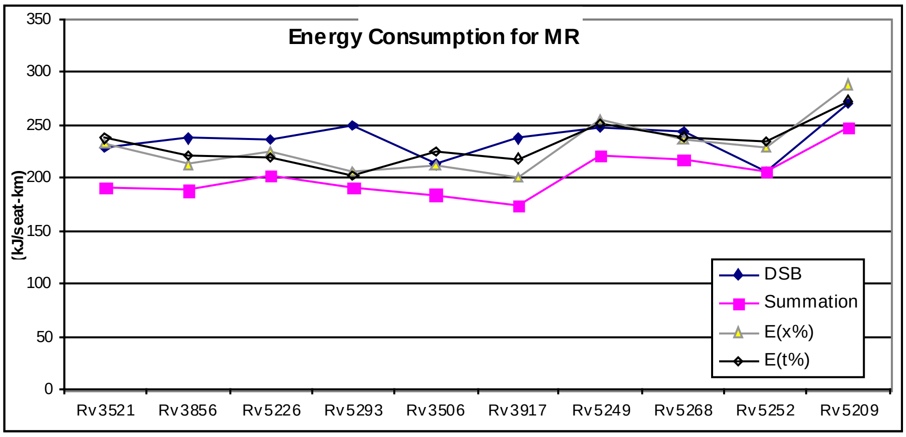


Figure 8.1 Energy consumption for the MR train set.

The figure shows that the values vary within an interval of about 50 kJ/seat km. The line titled DSB, shows the actual consumption from DSB. The relative changes from train to train are well predicted.

The general picture from Figure 8.1 indicates that the worst agreement is actually with the conventional detailed simulation summed throughout the actual driving pattern. The difference between the reference and calculations is on average 15% with a range between 5 and 25%. For $E(x_{\%})$ and $E(t_{\%})$ the difference on average is 7%, a little larger for $E(x_{\%})$. The largest differences are 15 and 12% respectively.

For the locomotive powered passenger trains the picture is quite similar to the MR.

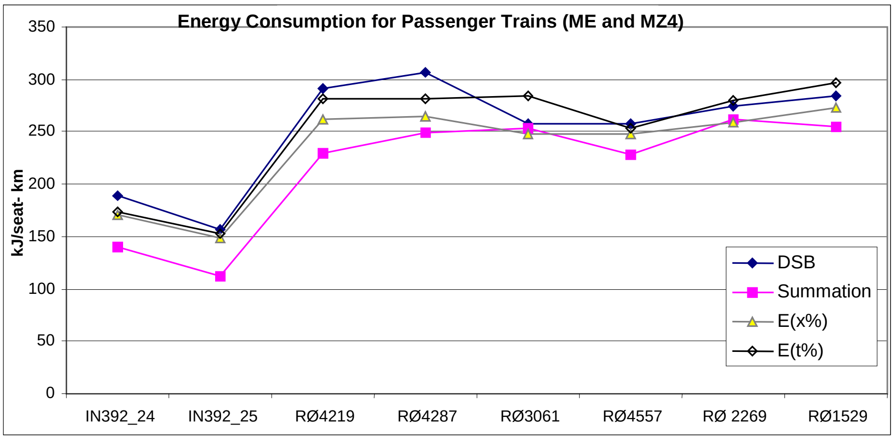


Figure 8.2 Energy consumption for locomotive powered passenger trains.

The first two are express trains, after which follow the two regional trains powered by ME. The final four use the MZ4 locomotive for power.
An average variation of 15% is found for the detailed simulation, while for $E(x_{\%})$ it is 7% and for $E(t_{\%})$ 8%. In general, $E(t_{\%})$ gives the highest values, the summation of the detailed simulation gives the lowest values.

For goods train, the same picture as the passenger trains is seen. The first 11 trains in Figure 8.3 are post trains, while the last three are normal goods trains.

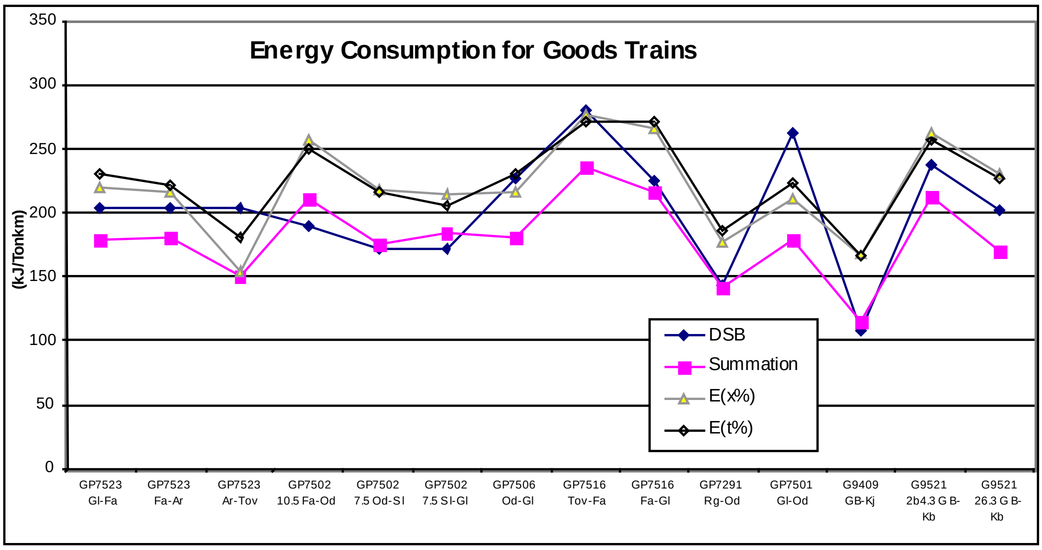


Figure 8.3. Energy consumption for goods trains

In contrast with the passenger trains, better results are achieved in the detailed calculation, where there is an average deviation from of about 13 % from DSB's values.

The matrix method gives an average variation of about 16%, again with the E($t_{\%}$) values being slightly higher than E($x_{\%}$). The deviation varies between 0 and 25 % for E($x_{\%}$), E($t_{\%}$) and DSB's values. The variation is greatest for the goods trains. In one single case (GS4909) a deviation of 32%, was found.

Emissions

Figures 8.5 and 8.5 show the CO_2 and NO_x emissions for the MR operation. The corresponding results for CO, HC and PM are shown in Appendix 7. Only a very few SO_2 emissions were available from DSB, so if was not deemed appropriate to include them.

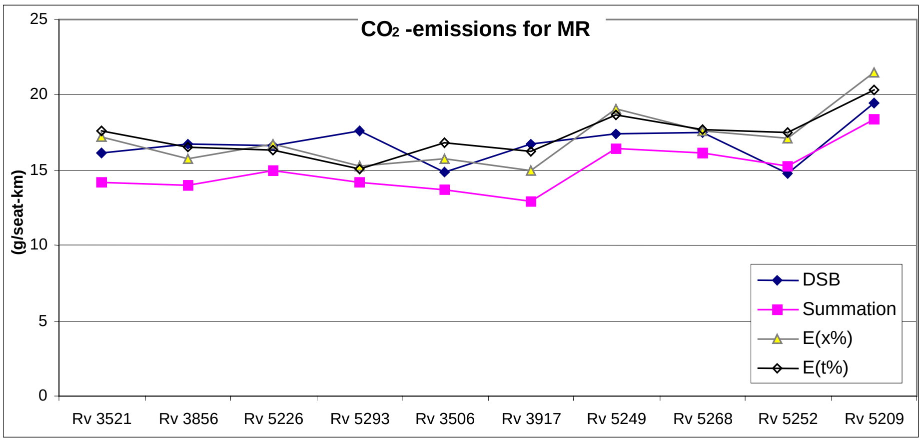


Figure 8.4 CO_2 emissions from MR

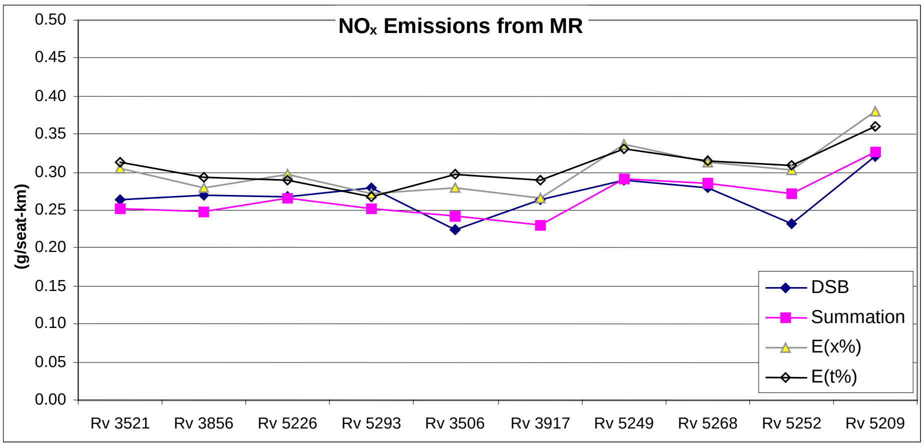


Figure 8.5 NO_x emissions from MR

The general pattern is close to that of the energy consumption, which is expected in the case of since the model uses average emissions factors on the basis of g/kg fuel. The only variation in trends then would be from the measurement data, which is obtained from condition dependent emission factors. This is only relevant for the NO_x emission.

The average deviation for the detailed model is 11% for CO_2 and 6% for NO_x. For $E(x_{\%})$ the differences are 7% and 13%, respectively and for $E(t_{\%})$ they are nearly the same 6% and 13%.

It should be noted that the differences for the energy consumption and emissions are not the same. This is because the values from DSB are from the loading collective, which used diesel oil consumption for each operating mode individually. Table 8.3 shows the average deviations of the energy consumption and emissions from the values from DSB.

	Detailed	$E(x_{\%})$	$E(t_{\%})$
kJ/ton km	0.15	0.07	0,07
CO_2	0,11	0.07	0.07
CO	0.27	0.21	0.20
NO_x	0.06	0.11	0.13
HC	0.62	0.57	0.57
PM	0.16	0.18	0.17

Table 8.3 Relative differences between predictions of different methods and results from DSB for the MR train unit.

The agreement between all approaches is within 20 % for all emissions and the energy consumption, with the exception of the HC emissions. This in discussed at the end of this chapter.

For locomotive powered passenger trains, similar results are shown in Figures 8.6 and 8.7. The results resemble those of the MR described above.

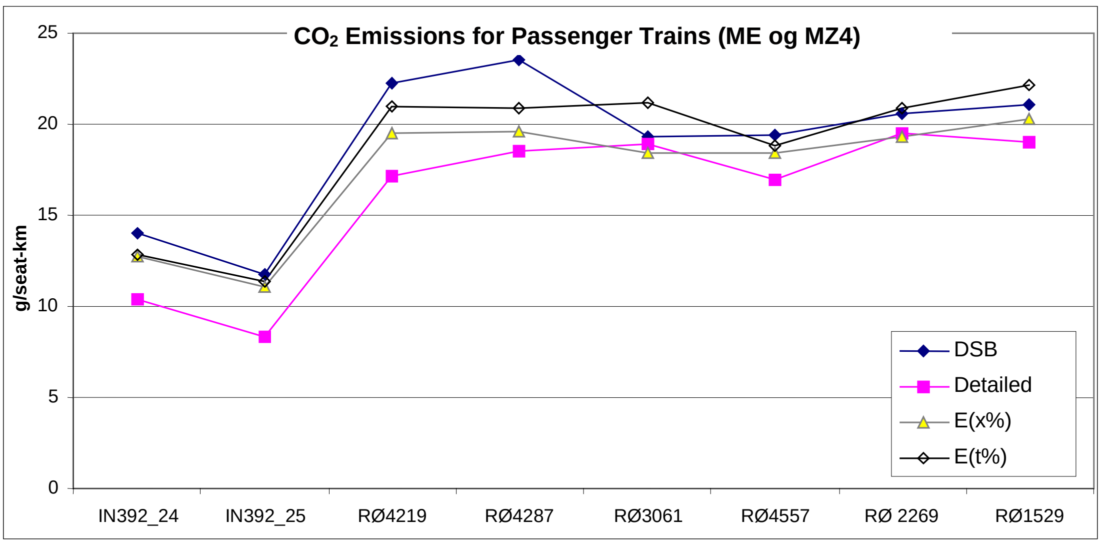


Figure 8.6 CO_2 emissions from locomotive powered passenger trains.

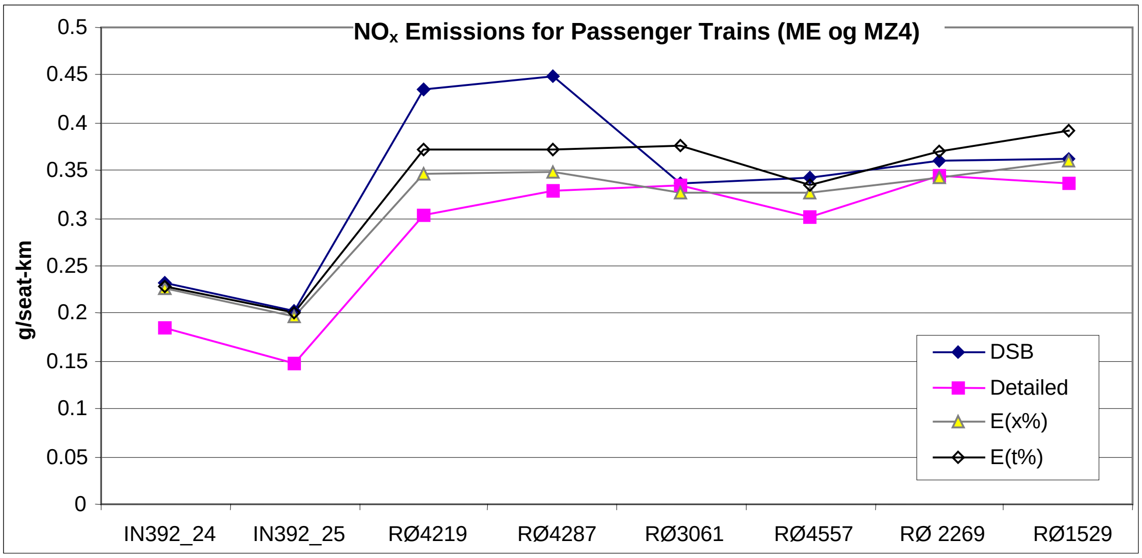


Figure 8.7 NO_x emissions from locomotive powered passenger trains.

The deviations are generally the same for the two emissions types. For CO_2 the average values for the detailed simulation, $E(x_{\%})$ and $E(t_{\%})$ are 15%, 8% and 9% respectively. For NO_x the corresponding values are: 16%, 9% and 10%.

The figures show that there are some individual variations up to about 25%. Table 8.4 shows the deviations for energy consumption in kJ/seat-km and all emissions in g/seat-km.

	Detailed	**$E(x_{\%})$**	**$E(t_{\%})$**
Energy	0.15	0.07	0.05
CO_2	0.16	0.08	0.06
CO	0.18	0.22	0.23
NO_x	0.16	0.08	0.07
HC	0.25	0.28	0.19
PM	0.31	0.38	0.41

Table 8.4 Relative differences between predictions of different methods and results from DSB for the locomotive powered passenger trains.

The table shows that there is good agreement for all emissions with the exception of HC and CO. The emissions factors in Table 1 were not specially adapted to DSB's conditions, indicating that general emissions factors can be used satisfactorily.

For goods trains, the average results lie within 80 and 90 % of DSB's values, that is the deviation is between 10 and 20%. The detailed simulation here gives the best agreement with DSB's values and the greatest difference is found with $E(x_{\%})$.

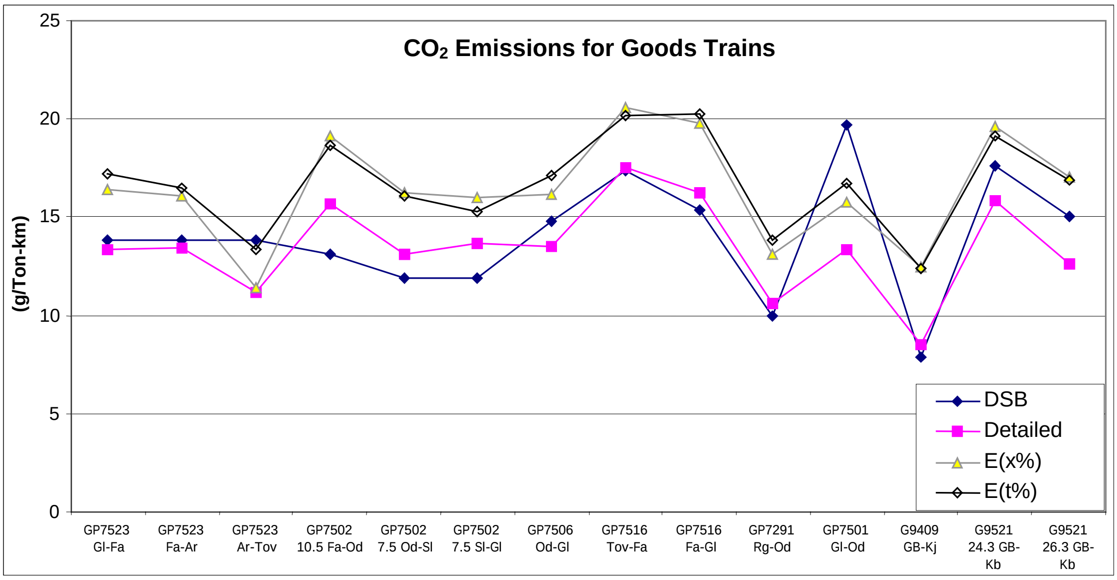


Figure 8.8 CO_2 emissions for goods trains

Relative to DSB's values, the deviations for the detailed simulation, $E(x_{\%})$ and $E(t_{\%})$ are, 11, 20 og 19% respectively. The general trends or relative emissions between the different operations are reproduced by all methods, indication that relative trends can be estimated with any of the three simulation methods. With these simulations, the matrix-based calculations have a tendency to be on the order of about 15% higher than the actual emissions.

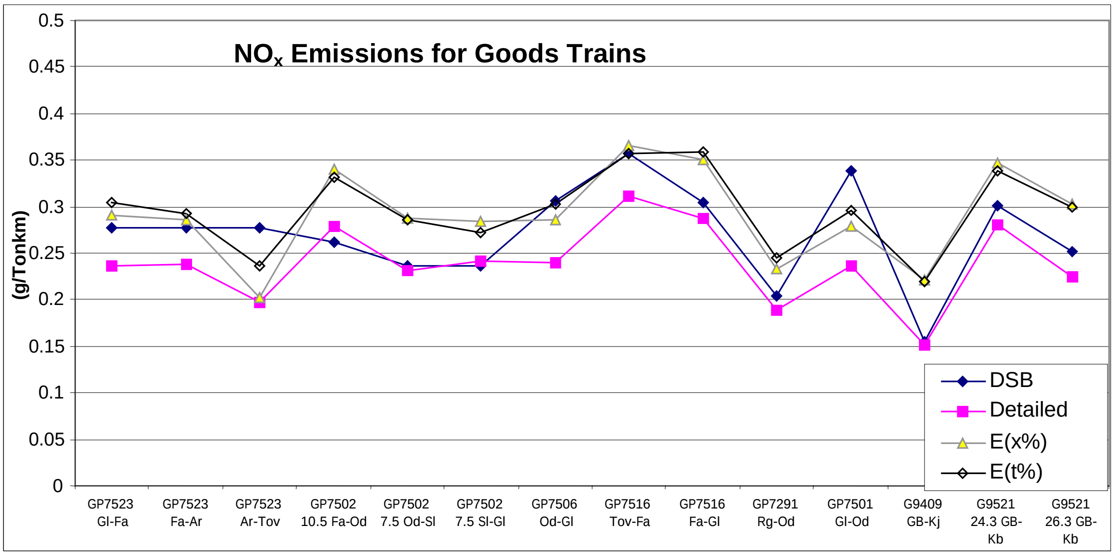


Figure 8.9 NO_x emissions for goods trains

The general trends for NOx emissions from goods trains, shown in Figure 8.9 are similar to those of the CO_2-emissions. For the detailed method, $E(x_{\%})$ and $E(t_{\%})$ the average deviations from DSB's values are 12, 15 og 13% respectively.

Table 8.5 shows the differences between simulate results and those from DSB for all emissions and energy consumption for goods trains.

	Summation	$E(x_{\%})$	$E(t_{\%})$
KJ/Ton km	0.12	0.15	0.14
CO_2	0.11	0.20	0.19
CO	0.25	0.36	0.37
NO_x	0.12	0.15	0.13
HC	0.18	0.31	0.32
PM	0.30	0.40	0.41

Table 8.5 Differences between simulated and experimental emissions and energy consumption for DSB goods trains.

As was the case for the locomotive powered passenger trains, the differences are greatest for CO, HC and PM. Since the deviations are of about the same as for the passenger trains, it is possible that the emissions factors used in the model do not agree with the actual emissions values for the MZ4 and ME locomotives.

For MR the particulate emissions were within 25% of DSB's values. For CO the deviations were about the same as for the MZ4 and ME. On the other hand, the simulated HC-emissions for the MR were only about 40%, of actual values from DSB.

Table 8.6 shows the emissions factors used in the model relative to the average values from DSB. The results are averaged over all operating modes for specific operations, which gives different emissions factors for the same engine under different operation types. The model factors used were from (Jørgensen and Sorenson, 1997).

	CO_2 [g/MJ]	SO_2 [g/MJ]	NO_X [g/MJ]	HC [g/MJ]	CO [g/MJ]	Partikler [g/MJ]
ME, Passenger	76.54	0.02	1.47	0.06	0.23	0.05
MZ4, Passenger	74.4	0.017	1.292	0.046	0.273	0.051
ME, Goods	76.15	0.017	1.496	0.059	0.182	0.053
MZ4, Goods	72.53	0.017	1.323	0.084	0.312	0.132
RV with MR	71.445	0.017	1.116	0.181	0.343	0.077
Models	74,44	0,075	1,32	0,066	0,246	0,076

Table 8.6 Actual emissions factors for the different train types compared to model values.

For CO the emissions factors are similar, and the deviation of about 25 % for the locomotive powered trains is likely due to other factors. The most likely is that the CO emissions are much more dependent on specific engine conditions than CO_2 emissions. This is known from other diesel engines (Heywood, 1988). For example, CO emissions at idle can be 10 times larger than those for medium loads. On the other hand, emissions factors from both goods trains and MR vary from the DSB results by between 20 and 30 %, which is also seen in the simulation results. The error is then only due to the CO emissions factor. The emissions factor for HC is in relatively good agreement with the ME locomotive, and the other hand, there are differences of 20 and 30 % for goods and passenger trains with the MZ4 respectively. For the MR the variation is over 60%, which is in agreement with the simulation.
The particulate emissions are identical for the MR. For the MZ4 with passenger trains and the ME, the difference is about 30% and for goods trains with MZ4 the difference in 40%, which is also in agreement with the simulations.

There is a question of which emissions factor is used. For CO_2 and NO_x average values appear to be adequate. For HC, CO and PM, it would be an improvement to use equipment dependent emissions factors. Given the historical difficulty in obtaining emissions factors and other relevant information from railway organizations, this appears to be an overly optimistic approach. Similarly, one could attempt to use operating condition specific emissions factors. The difficulties here are similar, especially for fleet operation, though it might be possible to obtain some data for an individual train. Given these difficulties, the model is programmed using average, fuel specific emissions factors. They can readily be changed in the spreadsheet.

8.3 Summary

In general the model calculations give good results for the passenger trains investigated. Variations between model calculations with the operations matrix and the results from DSB are less than 10% for passenger trains. Using a detailed simulation, the differences were around 15%. Since the purpose of the calculations was to investigate the utility of the matrix approach, it can be said that the method is viable. For goods trains the results were not as good. There was a larger spread in results but in most cases the variation from the DSB numbers was between 15 to 20 %. In this case the detailed simulation gave better agreement than the operation matrix approach.

It has been shown possible to make good estimates of energy consumption and emissions for different types of trains in spite of a number of simplifying assumptions:

- All operation with negative acceleration was not included in the calculation. Typically the energy consumption and emissions are determined by operation of between 50 to 70% of the operating time or distance.
- Traction efficiencies were based on average values.
- Gradient effects were not included, though in Denmark the terrain is generally flat.
- Wind and tunnel conditions were not included.
- Only standard rolling, aerodynamic and acceleration resistance was included.

There can be several reasons for the larger differences with the goods trains, some of which are:

- Inexact values for loading. That is, the amount of goods on the trains.
- Approximate values for the air resistance coefficient C_L.
- A less even operation patter for goods trains compared to passenger trains.

In addition, it would be advantageous to use specific emissions factors for individual types of equipment, especially for CO, HC and particulate emissions.

Classification of operation relative to DSB's values and calculation.

Since most of the goods trains considered are post trains with uniform wagons, the problems with the resistance values could be expected to be smaller. In general, the post train simulations did not give better results than for the other goods trains, where the uncertainty of the air resistance coefficients was greater.
Uncertainties regarding the goods weight and other things were encountered in a few cases missing or misleading values. There were 3 cases, where encountered where the train arrangement was changed during the trip, and in the simulation was divided into

corresponding portions. Only one measured value was available for the entire trip, even though there were cars taken off and added to the train enroute.

The overall arrangement of the train is illustrated more closely in Chapter 14 for all types of train. It is difficult to evaluate the importance of this factor in the agreement between measurements and models. Regional train can also have varying arrangements, especially where the net is heavily loaded and of limited capacity.

8.4 Evaluation of model parameters

The models utilize a variety of input data and information. Several of these factors are necessarily connected with uncertainties that influence the model result to some degree. In the following, the influence of a series of factors on the calculated results is investigated for the conditions in Chapters 8.1 and 8.2.

In order to give a picture of these uncertainties, the following simulations were performed. This is performed by calculating the energy consumption for different values of the parameters of interest. The factors investigated are:

- Goods weight and number of passengers
- Interval size for the speed acceleration matrix
- Traction efficiency
- Gradients
- Head wind +/- 15 m/s
- Aerodynamic and rolling resistance coefficients: C_L and C_R

Some of the factors are relevant for both goods and passenger trains, while a few are only relevant for one of the types. For clarity, only two runs are considered. The choice of these runs was made according to the following criteria:

- The range of speeds and accelerations should be a large as possible.
- C_L and C_R should be fairly well known.
- The train weight and/or number of passengers should cover a relatively large interval.
- The gradients should be known and preferable about 0 +/-10 m. or at most 0,1 ‰.

Based on these criteria, two runs were selected.

- RØ 4557. KBH - Kalundborg (Tare weight 412,5 tons 600 seats)
- GP7523. Glostrup - Fredericia (Tare weight 303 tons and goods weight 126 tons).

8.4.1 Evaluation of goods weight

Figure 8.10 and 8.11 show energy consumption in kJ/ton km and kJ/goods-ton km for the goods train. Calculations were performed for 5 different weights of goods: 80, 100, 125, 150 and 170 tons.

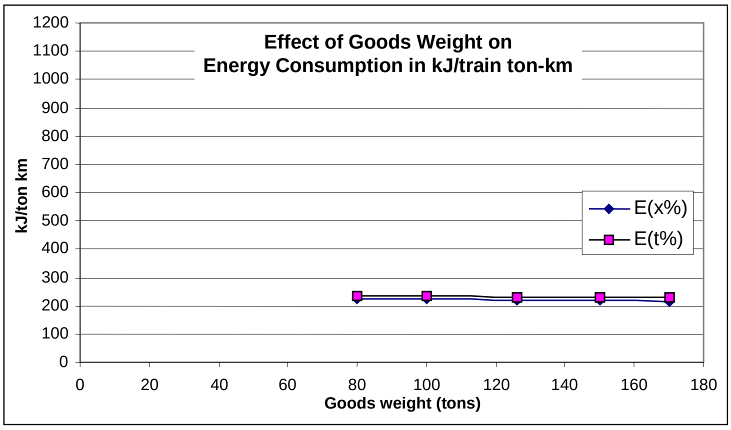


Figure 8.10 Effect of goods weight on total energy consumption in kJ/train ton-km.

Figure 8.10 shows that on the basis of total train weight, the weight of the goods has little effect on the specific energy consumption. Therefore, the energy consumption per basis of goods transported is strongly dependent on the loading factor, as is readily seen in Figure 8.10. Thus, for calculating energy consumption for goods transported, the loading factor is an important factor.

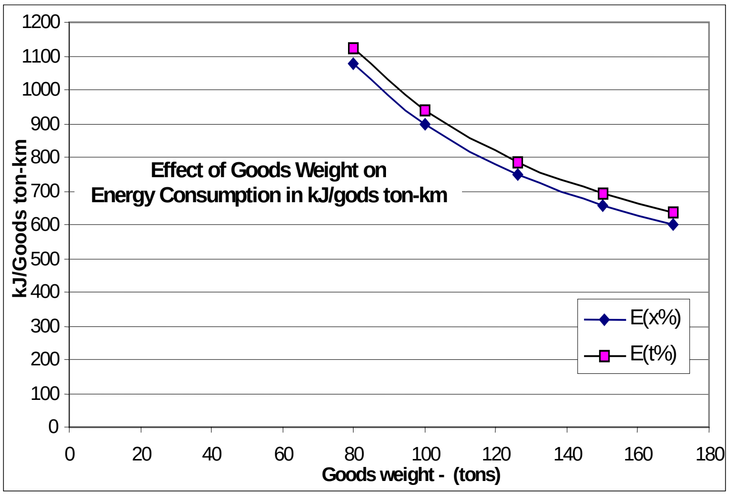


Figure 8.11 Effect of goods weight on total energy consumption in kJ/goods ton-km.

8.4.2 Evaluation of the number of passengers

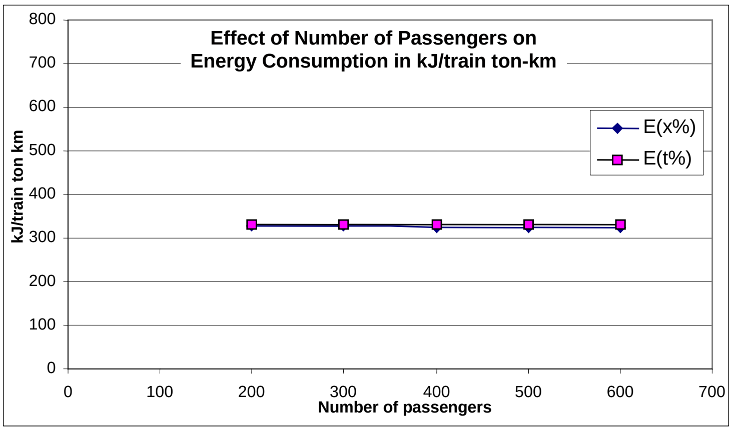


Figure 8.12 Effect of number of passengers on energy consumption in kJ/train ton-km.

It is common to calculate energy consumption for passenger trains on the basis of seat-km. This is close to the total weight basis, since passenger weight is normally small in relation to total passenger train weight. Typical passenger trains have a weight of about 1 ton per seat, as passenger with luggage totaling 100kg, only increases this figure by 10%.

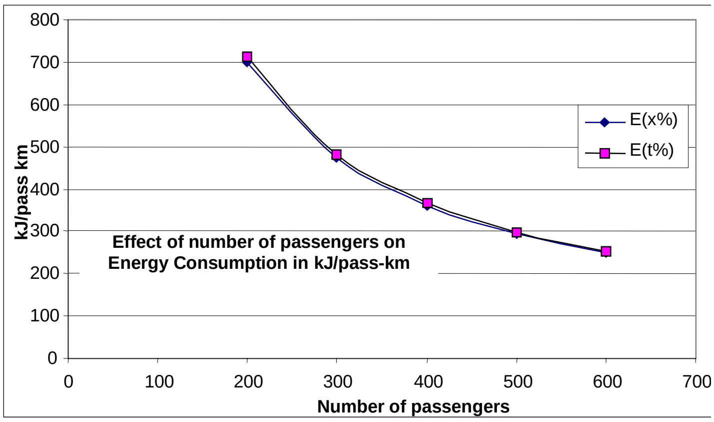


Figure 8.13 Effect of number of passengers in energy consumption in kJ/passenger ton-km

It is expected that only the energy consumption per passenger km will be affected by the number of passengers on the train. For the chosen passenger train route, calculations were performed for 300, 400, 500 and 600 passengers. The results are shown in Figures 8.12 and 8.13.

As was the case for the goods trains, there is no difference in the energy consumption per train ton-km as the number of passenger trains, as is shown in Figure 8.12. This is because the weight of the passengers is small in relation to the total train weight, and in addition, the weight of the passengers is included in the total weight, which is used to normalize the energy consumption.

As expected, when energy consumption on a per passenger basis is used, the occupancy is a very important parameter, and on this basis, is more important than many technical factors in determining the passenger specific energy consumption

8.4.3 Traction Efficiency

The average traction efficiencies for the two trains are 0.30 for the MZ4 powered passenger train and 0.35 for the ME powered goods train. Figures 8.14 and 8.15 show the changes in train energy consumption resulting from a variation in the traction efficiency. For each train, traction efficiencies of 20, 25, 30, 35, and 40 percent were. As expected, the energy consumption is significantly dependent on the traction efficiency. The curves are not linear, since energy consumption is the inverse of the efficiency, and at zero efficiency, an infinite energy consumption would result.

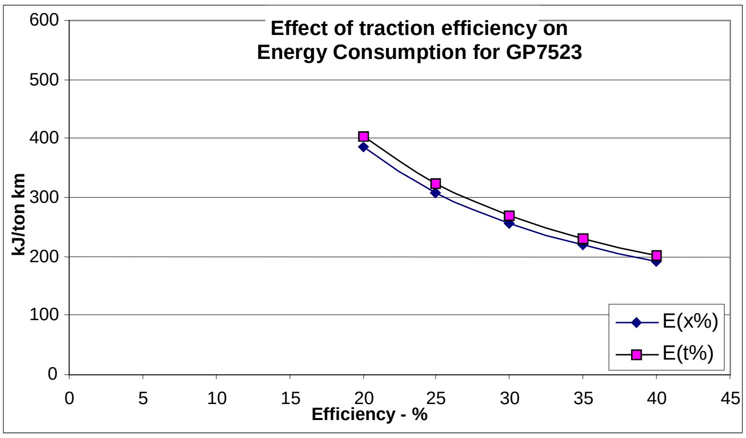


Figure 8.14 Effect of traction efficiency on energy consumption for a goods train.

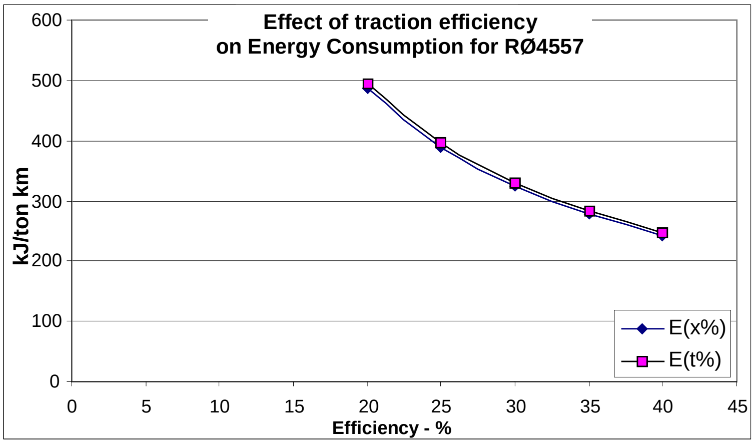


Figure 8.15 The effect of traction efficiency on energy consumption for a passenger train.

8.4.4 Gradients

Though the terrain of Denmark is flat, the effects of elevation are small. It is, however, possible to estimate the effect of differences in elevation from a simple theoretical point of view. If regenerative braking is not considered, the effects of elevation changes are shown in Figure 8.16 for the chosen goods trains. Overall height changes of ±50m, ±100m and ±200 m were included in the operation patterns, even though they exceed that possible in the terrain driven. Since the routes for the goods and passenger trains were different, these correspond to relative gradients between 0 and 1‰ for the goods train and 0 to 0 and 1,7 ‰.

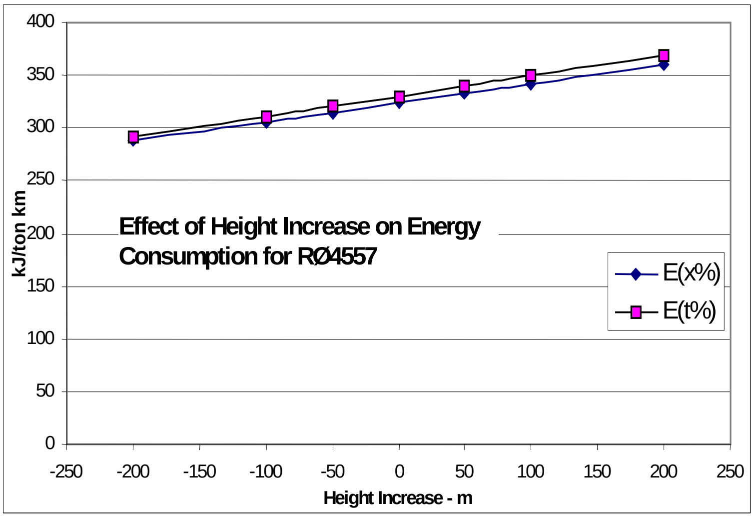


Figure 8.16 Effect of height increase for the operation of the passenger train, total trip length = 113km

The changes in energy consumption are essentially linear in the gradient for the modest grades included here. The energy consumption of the goods train on a ton-km basis is over 50% greater than that for the passenger train. Therefore, it might be expected that the relative contribution of the gradient could differ between the two train types. This is not the case, as Figure 8.17 shows. This is a figure shown the relative change in energy consumption for the two train types on the same curve. It is seen that

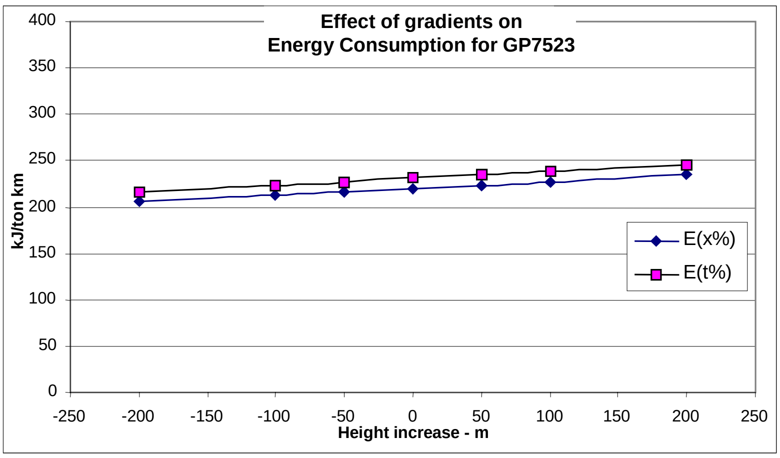


Figure 8.16 Effect of height increase for the operation of the goods train, total trip length = 211km

on a relative basis, there is no difference between the types. This is because the gradient energy consumption is proportional to the mass of the train, and when the total energy consumption is divided by the mass of the train, the gradient contribution depends only on the gradient. The acceleration and rolling resistance contributions are also proportional to the mass, and when normalized by train mass, depends only on the acceleration. In a similar way, though not exactly, the aerodynamic resistance increases with the train size. Therefore, the relative contribution of the gradient to the specific energy consumption is not dependent on train size, or in the cases shown type.

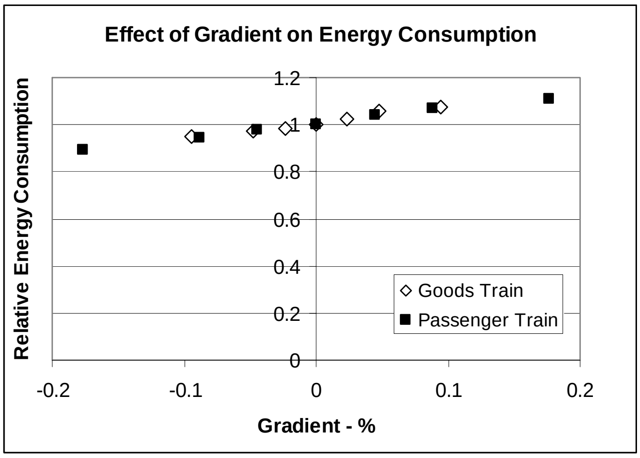


Figure 8.17 Relative changes in energy consumption for both passenger and goods trains.

Since the changes are symmetrical to zero gradients, the changes in energy consumption for transport on a stretch in both directions should be nearly independent of gradient. This is because trains going down will compensate for the energy consumption increase for trains going up. There are some assumptions here that may not always hold. One is that the amount of goods and passenger traveling in each direction is the same. The other is that there is no regenerative braking. In addition, the gradients considered are modest, and operation in steep gradients can affect the operation characteristics (speeds and accelerations). To evaluate this, actual driving patterns for steep gradients must be evaluated.

8.4.5 Wind direction

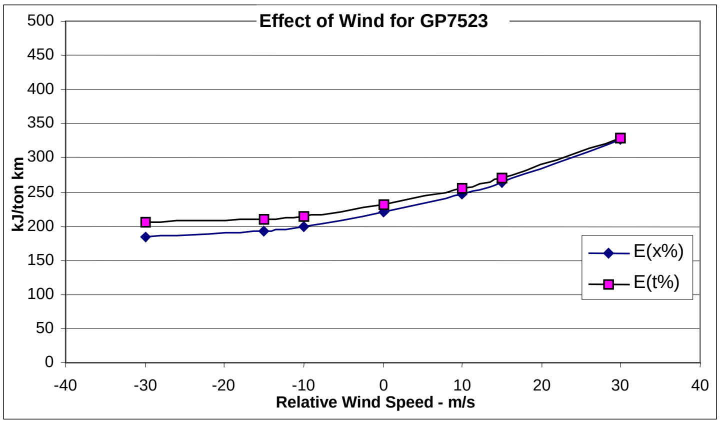


Figure 8.18 Effect of relative wind speed on energy consumption for the goods train.

As mentioned previously, all calculations were performed for wind still conditions. In practice, there is wind from all directions, and trains do not operate in a straight line on most routes. Therefore, it is of interest to show the effect of relative wind direction on energy consumption. Here the effects will be shown only in a head wind/tail wind fashion. In practice, side winds have an effect on energy consumption, both in terms of the relative wind velocity in the direction of motion, and on the drag coefficients. To investigate the effects of wind, relative wind speeds of +/- 10, 15 and 30 m/s have been used with 0 being the reference condition. This covers the range of moderate to extreme wind.

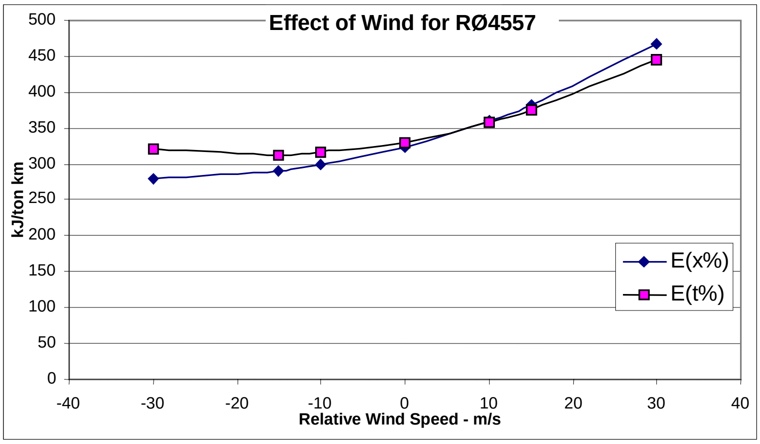


Figure 8.19 Effect of relative wind speed on energy consumption for the passenger train.

The figures show that a tail wind does not give a large reduction in energy consumption, even for strong winds. This applies to both of the trains. The wind resistance term is proportional to the square of the relative wind speed. So a head wind gives a dramatic increase in wind resistance, while a tail wind gives a dramatic decrease. In the case of the latter, aerodynamic resistance no longer plays such an important role, and the acceleration and rolling resistances dominate. Thus, the effect of wind becomes small for increasing tail wind speeds. A wind speed change of 10m/s gives a relative change in energy consumption of about 10%.

8.4.6 Driving resistance parameters

The post goods trains chosen to evaluate the effect of driving resistance parameters was GP7523. This is primarily due to the greater potential for variation of the resistance values for goods trains. Goods trains are composed of a variety of wagons, with different shapes, heights and arrangements. The aerodynamics resistance coefficient, C_L and the rolling resistance coefficient, C_R are evaluated separately.

The following values were used for C_L: 1.8, 2.0, 2.15, 2.3, 2.5, and 3.0 where 2,15 is the basis reference value calculated from the equipment specifications. This corresponds approximately to a variation in C_L of ± 50 %.

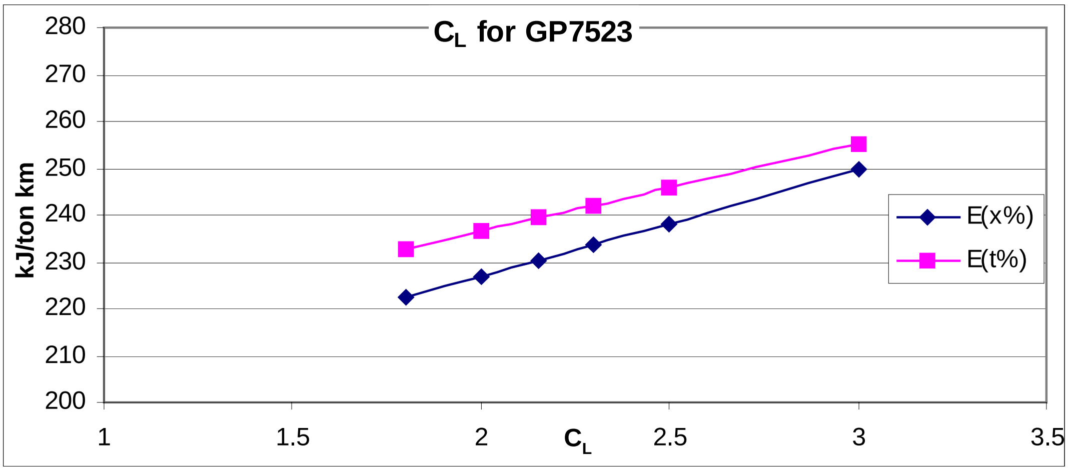


Figure 8.20 Energy consumption as a function of the aerodynamic drag coefficient for the goods train.

Figure 8.20 shows that the energy consumption is directly proportional to C_L. The energy consumption varies with between 10 and 12 % between the maximum and minimum values for C_L. This percent is about 1/5 of that of the variation in C_L.

For the variation in the rolling resistance coefficient, C_R the following values were chosen: $2.8 \cdot 10^{-3}$, $3 \cdot 10^{-3}$, $3.2 \cdot 10^{-3}$, $3.5 \cdot 10^{-3}$, and $3.7 \cdot 10^{-3}$. The results of Figure 8.21 show that the variation in the energy consumption as a function of the rolling resistance coefficient for the GP 7523 post goods train. For variation in the rolling resistance coefficient of ± 13 %, the energy consumption changes by about ± 3.3 %. The variation in the energy consumption corresponds to about 1/4 of the variation in the rolling resistance coefficient.

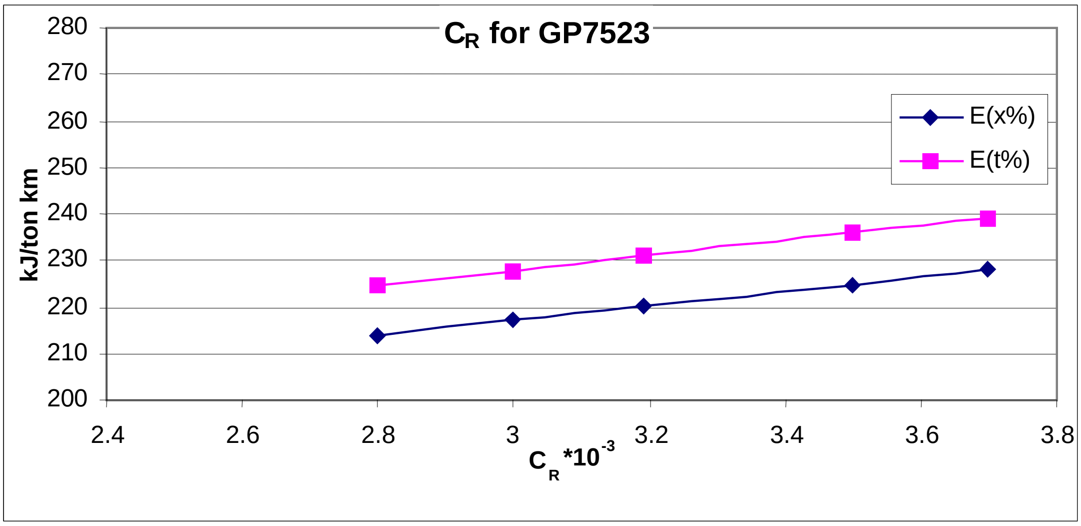


Figure 8.21. Energy consumption as a function of the rolling resistance coefficient for the goods train.

The operation of this particular train represents a mixed operation, dominated by neither steady state operation nor acceleration/deceleration. In the case of a train traveling long distances between stops, the results will be more sensitive to the rolling resistance parameters, since they determine steady state loading. On the other hand, for a train with large numbers of accelerations and decelerations (for example an urban train or metro), the rolling resistance would play a smaller role. This is because the majority of the energy consumption occurs under accelerations, where the train mass and propulsion efficiencies are the determining factors.

The calculation of C_R is thought to be relatively accurate, since there is not a great variation on the wheel types for these trains. C_L presents a larger opportunity for error, since the arrangement of the train can affect the flow characteristics, and the arrangement is not always known. The results of Figures 8.20 and 8.21 and the previous comparisons with DSB data indicate that the driving resistance characteristics of trains can be calculated to a good accuracy.

8.4.7 Simulation with variation in the operating matrix size

It is especially important to investigate the sensitivity of the model to the size of the operational matrix. That is, what is the size of each element in terms of variation in velocity and variation in acceleration? It is desirable to use a small number of elements in order to minimize calculation time, but yet use a resolution that will be adequate to calculate typical changes in operation patterns.

In the previous investigations, the operating pattern has been divided into 150 elements. The velocity has ranged from 0 to 150 km/h in intervals of 10 km/h and the acceleration from 0 to 1.0 m/s^2 in intervals of 0.1 m/s^2. Those portions of the driving pattern where the acceleration is negative have not been included, since these can approximately be said not to give any significant contribution to the total energy consumption. Assuming that the train is coasting, the consumption is that of idle operation, and the fuel consumption is limited. Appendix 2 shows an operation collective where this is the case for the two trains analyzed.
Figure 8.22 shows the acceleration as a function of the speed for RØ4557, where only the positive accelerations are included.

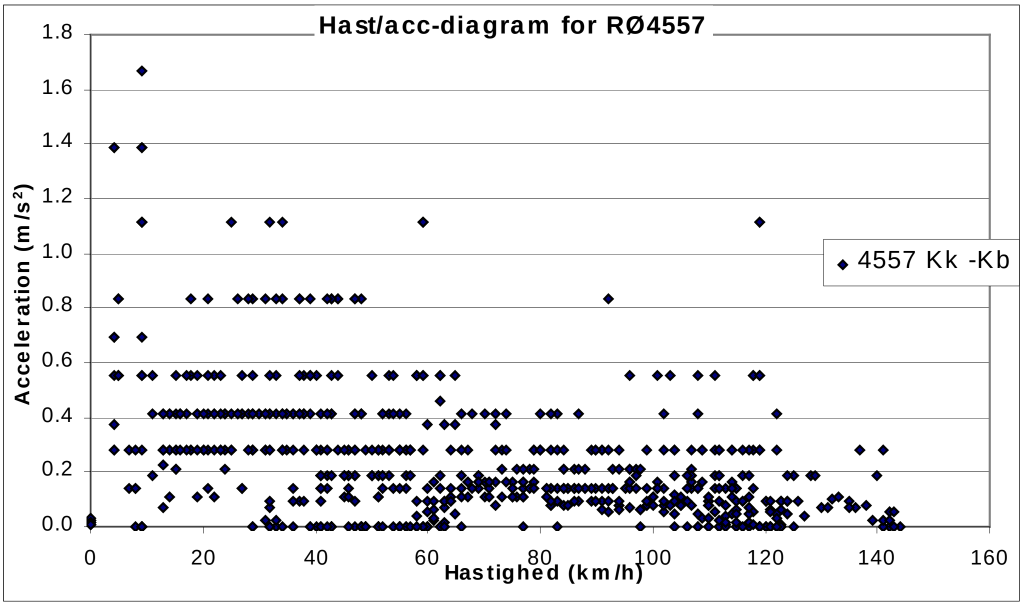


Figure 8.22. Acceleration as a function of velocity for RØ4557

In the following, this operating pattern will be analyzed for the RØ4557 train using different resolution in the acceleration-velocity matrix. The variations in the speed er acceleration size will be made with a constant value of the other parameter.

8.4.8 Speed

The driving pattern for the above figure was divided into 15 intervals of 10 km/h. In addition, 10 acceleration intervals were used from 0 to 1 m/s^2. The entire operating characteristic was then divided into 150 elements. In the following, the energy consumption per ton-km was calculated using 25, 15, 10, 5, 3 and 2 intervals for the speed. The results are shown in Figure 8.23, where 10 acceleration intervals were used. The results indicate that there is not a major effect due to the speed interval size, al long as there are more than 5 speed intervals. Even down to 3 intervals the effects are small. A division into 15 intervals with a spread in speeds of 10kph seems to be more than sufficient.

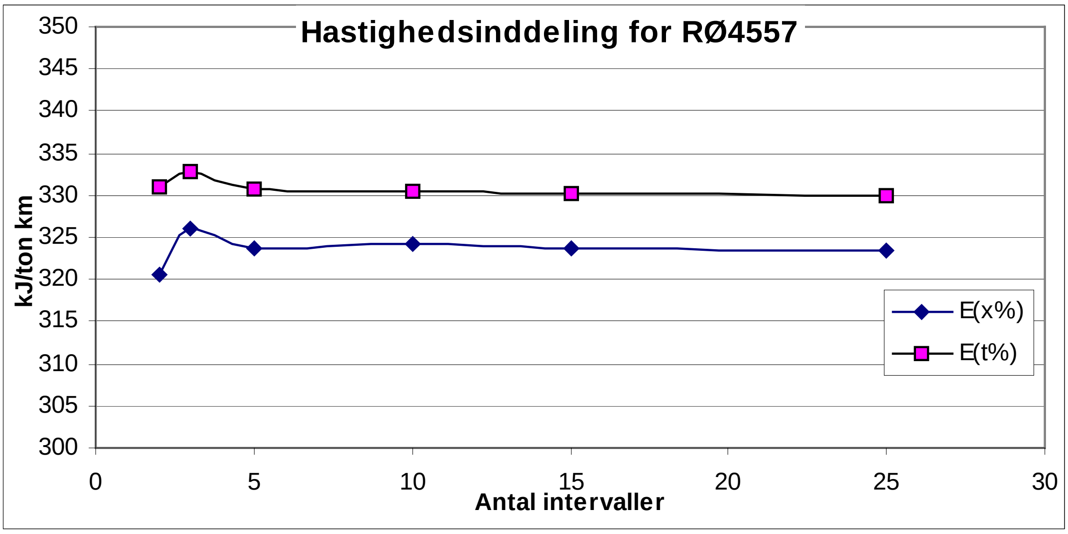


Figure 8.23 Effect of speed interval size on the calculated energy consumption.

8.4.9 Acceleration

In contrast to the speed intervals, the energy consumption is sensitive to the size of the acceleration interval. For the passenger trains shown, there must be more than 10 intervals before the results become independent of interval size. This means that the absolute interval spread should be less than 0.20 m/s^2.

In general, it appears that if the general guideline of speed intervals of 10 km/h and acceleration intervals of 0.2 m/s^2 or smaller are used accurate estimates of energy consumption for driving patterns or statistical distributions should be calculated with acceptable accuracy.

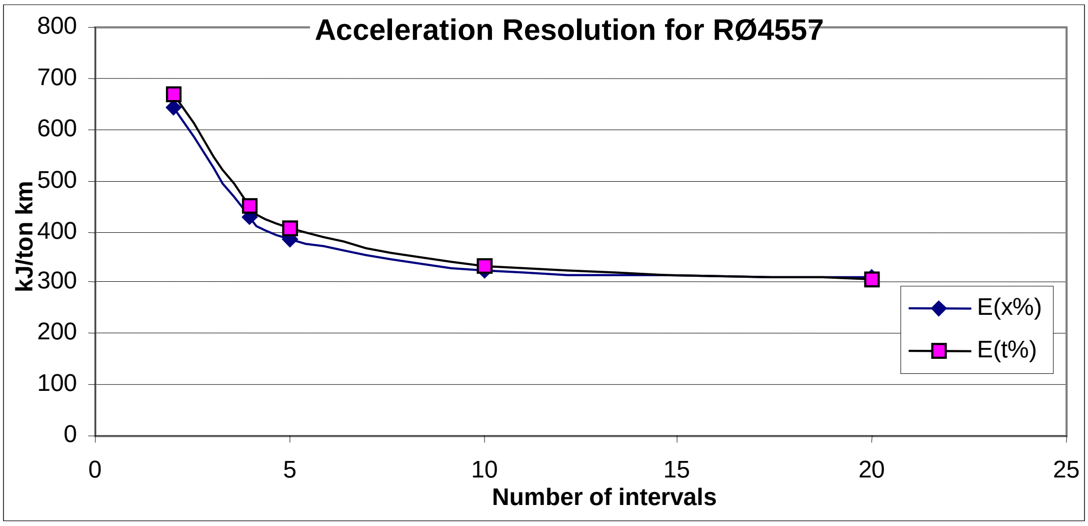


Figure 8.24 Energy consumption as a function of acceleration interval size.

9 Summary of Model

A model has been constructed that can estimate energy consumption and emissions from rail traffic. Calculations can be made on the basis of knowledge of operating characteristics distribution with respect to either time or distance. The model has been evaluated on 18 passenger train routes and 12 goods train routes. The results were compared with energy consumption and emissions calculated on the basis of measured operation collective for engine power, and measured engine energy consumption and emissions.

For the passenger trains, the model was able to calculate energy consumption within 15%. For goods trains, the variation was slightly higher. NOx emissions could be estimated to a similar level of accuracy using average emissions factors applied to the total energy consumption and not to the individual operation points. Emissions of CO, HC and particulate matter are more sensitive to individual operation conditions and specific engines, and can be estimated to within 25-30 % using average emissions factors.

It is concluded that the concept of dividing operating patterns into a speed-acceleration matrix and calculation energy consumption from train data and estimates of rolling resistance parameters is viable. The emissions calculation included technical factors in a correct, but not overly complicated manner. It is possible to apply the model to a wide range of fleets, from a single run to a national average for a train type. The requirement is that a reasonable estimate of the temporal or spatial distribution of the operating condition of the type of train analyzed is known.

One possibility for obtaining data is the use of timetables. In this case, distances are either known or readily available, and travel times directly given. With standard corrections for acceleration/deceleration times or distances, operating statistics are readily available for almost any passenger route for schedule traffic. Goods traffic travel data is not generally available in this form, though some typical operations are shown in the report.

10 Idle operation significance.

As mentioned in the section concerning the models, operation at idle is not included. The driving patterns that are simulated are divided into acceleration and speed intervals, where neither deceleration nor operation with the train stopped are included. The purpose of this section is to evaluate how much of the energy consumption and emissions are related to operation at idle. All of the load collectives used were calculated by DSB.

The driving patterns used are RØ4557, GP7523 and RV5249, which were also used in connection with the test of the model principle. RØ4557 and GP7523 were also used in the evaluation of the model parameters. All of the operations are representative. That is, they do not differ in any significant way from other similar operations. The total load collectives for the three operations are shown in Appendix 2.

10.1 RØ4557. Østerport-Kalundborg

Table 10.1 shows the energy consumption and the emissions for the different operation steps.

Controller step	Time	Dist.	Fuel Use	CO_2	NOx	HC	CO	Particles
	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)
0	51	34	4.94	4.82	5.90	21.93	13.19	5.36
1	2	3	0.27	0.26	0.30	0.68	0.32	0.19
2	3	4	0.95	0.91	0.76	1.23	0.71	0.89
3	2	3	1.47	1.42	1.37	1.35	0.61	1.59
4	8	12	7.54	7.43	7.36	5.89	2.52	9.26
5	3	4	3.34	3.28	2.95	2.48	1.54	4.88
6	2	3	3.49	3.47	3.03	2.42	2.83	4.23
7	2	2	4.49	4.52	4.51	3.27	4.26	4.88
8	28	35	73.50	73.89	73.83	60.74	74.04	68.72
I alt	101	100	100.00	100.00	100.00	100.00	100.00	100.00

Table 10.1 Percentage load collective for the MR train.

The load collective shows that over half of the driving time occurs at idle. It is seen that for the fuel, CO_2, NO_x and particle emissions, idle operation is responsible for only about 5%. For HC and CO idle produces about 22 and 13% of these emissions respectively. That is, large portions of the HC and CO emissions occur at idle and at full load (step 8). Operation at full load accounts for about 30% of the total operation time. It is here that the main part of the energy consumption and emissions are found. For the fuel consumption, CO_2, NO_x and CO about 75% of the consumption/emissions occur at full load. The shares of the different operating steps for the total operation are typical for locomotive powered regional trains. For the international trains the conditions are different. The share at full load is nearly the same, but the relative amount of idle operation is significantly reduced, which is due to the reduced number of stops per km.

10.2 GP7523. Glostrup-Fredericia

Table 10.2 shows the energy consumption and the different emissions on a relative basis for the different operating steps of the GP7523.

Controller step	Time	Dist	Fuel	CO_2	NOx	HC	CO	Particles
	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)
0	37	27	4.84	4.67	5.38	14.36	6.85	1.55
1	6	6	0.74	0.71	0.85	1.95	0.72	0.25
2	4	3	1.26	1.22	1.25	1.93	0.74	0.46
3	6	7	3.68	3.54	3.81	4.31	1.35	2.40
4	11	14	10.06	9.94	10.84	9.91	2.91	9.32
5	9	10	11.51	11.39	12.20	9.93	3.34	14.08
6	7	7	10.62	10.60	11.07	9.07	4.40	10.78
7	1	2	3.08	3.10	3.02	2.53	3.57	3.16
8	20	23	54.21	54.84	51.58	46.01	76.11	58.00
sum	101	99	100	100	100	100	100	100

Table 10.2. Percentage load collective for the ME+goods train.

The tendencies are basically the same as RØ4557. About 5% of the energy consumption, CO_2 and NO_x emissions are related to idle operation. This is in spite of the fact that the engine operates at idle 37% of the time.

10.3 RV5249. Aalborg-Frederikshavn

Finally, a corresponding load collective is shown for operation with the type MR. The train is the RV5249.

Controller step	Time	Dist.	Fuel	CO_2	NOx	HC	CO	Particles
	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)
0	41	26	5.17	5.81	3.56	54.92	49.28	43.85
1	3	3	1.22	1.16	0.95	4.55	3.32	3.96
2	4	4	2.41	2.22	1.64	5.25	5.74	4.44
3	1	2	1.09	1.10	0.88	1.39	1.55	1.24
4	9	13	9.28	9.12	8.43	5.71	6.63	6.13
5	1	2	1.39	1.41	1.48	0.55	0.59	0.57
6	8	13	13.25	13.34	14.91	3.80	3.84	4.00
7	33	37	66.18	65.84	68.15	23.84	29.05	35.81
sum	100	100	100	100	100	100	100	100

Table 10c. Percentage load collective for the MR train, RV 5249.

Once again, a large portion of the operating time (41%) occurs with the train's engine at idle. About half of the emissions of HC and CO are emitted during this condition. 33% of the time passes with the engine at full load, where about 65% of the energy consumption, and CO_2 and NO_x emissions are found. For the other types of emissions, between 25 and 35% of the emissions occur at full load.

10.4 Summary

An analysis of the load collectives shows that the omission of idle operation has no noticeable influence on the simulated energy consumption. The energy consumption at idle is generally under 6% of the total for the analyzed cycles, which must be seen to be too small to have a noticeable effect on the results.

The emissions of CO2 and NO_x are distributed over the operation steps in almost the same manner as the energy consumption. That is, the CO_2 and NO_x emissions are proportional with the energy consumption, which is expected especially for the CO_2.

11 Analysis of driving distributions

The following will illustrate the distribution of the operating condition of the trains for some of the simulated operations. This can be used for different purposes. First and foremost it can give a good illustration of the actual operation.
The most obvious parameters in the study are speed and acceleration and either time or distance. A distribution gives an overall picture of the operation, and shows the general tendencies. On the other hand, the instantaneous picture of the operating pattern gives a more diffuse picture that does not necessarily emphasize the actual tendencies.

The picture desired is how the operation for different types of trains is organized and the relations between the different types of trains. Part of the information is what portion of the operating time is spent in the different modes (accel., etc.), but also the relationship between the speed and acceleration. That is, what accelerations are found for the different speed intervals, and what is their frequency. From this it will be shown:

- How much of the operation occurs with the different speeds?
- What are the most common speeds, and how large are the accelerations the train can accomplish?
- In which speed intervals are the variations in speed greatest and how large are the variations?

The relation between acceleration and speed can be investigated from either a temporal or spatial point of view. Often there is good agreement between these two points of view. Since a complete description of a driving pattern is very extensive, the discussion is limited to four trains in three train types:

- Inter-city train. IC 545 København-Odense. The train consists of an ER-set. There are eight stops, max speed: 158 km/h.
- Regional train. Re4557. Østerport-Kalundborg. MZ4 + eight wagons. 11 stops, max speed: 144 km/h.
- Goods train. GP7523 Glostrup-Fredericia. ME+ seven post wagons, two signal stops, max speed: 140 km/h.
- Goods train. GS7499 GB-Århus. The train is powered by an ME with different number of wagons between each stop. Stops in Ringsted and Fredericia. In addition there are four signal stops, max speed: 120 km/h.

The regional and goods trains are the same trains that were used in connection with the test of the simulation model. These trains were chosen to give a reasonably complete coverage of the types of train available. The distributions for the three types of trains will be expected to have a unique appearance. The IC train operates with higher speeds and has relatively few stops, which will give a distribution concentrated around the higher speeds, for normal operation. The regional train operates with lower speeds, and has many stops, which should give a broader, more varied distribution. The first goods train, which is actually a mail train, has about the same speed as the regional train, but with much fewer stops. In this fashion, it is intermediate between the IC regional trains. The last goods train operates with slightly lower speeds than the other three trains. In addition is has many stops along the route. The post train can then be considered to represent a through goods train.

Several types of diagrams are used to give a thorough picture of the operations. The illustration of the distribution is made in the form of a 3D-plot, with different graphs and pie charts as supplements. The same 3D-plots are shown in larger format in Appendices 8-13.

11.1 IC 545 København-Odense.

The most basic information is given in a speed-time or speed-distance diagram.

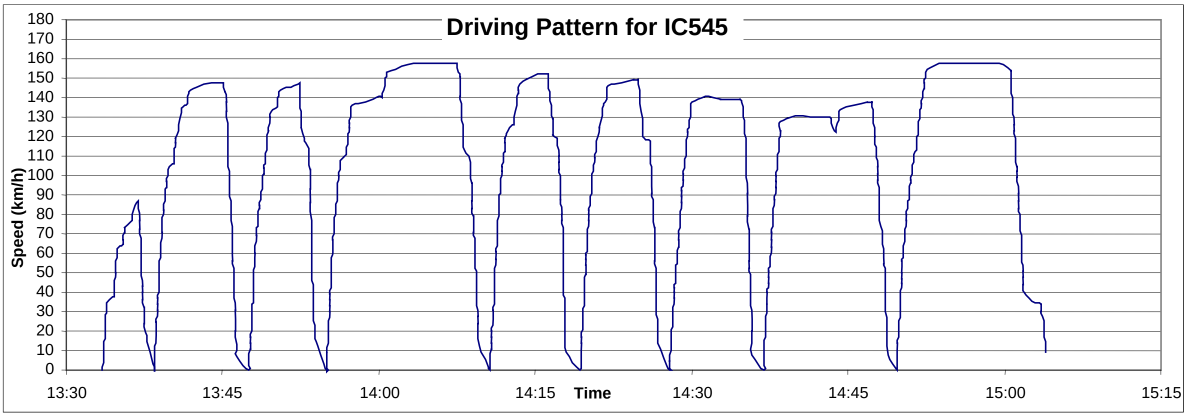


Figure 11.1. Speed as a function of time.

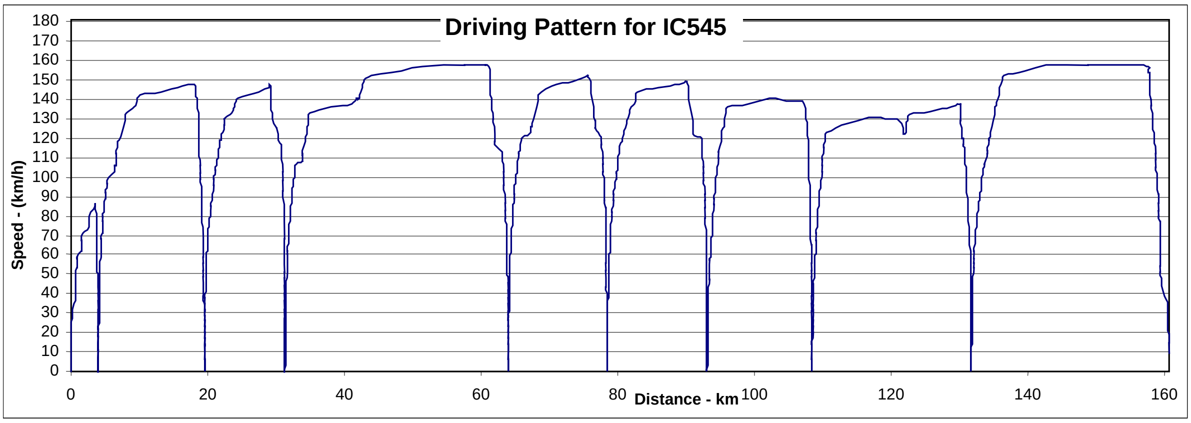


Figure 11.2. Speed as a function of distance.

It is apparent from figures 11.1 and 11.2, that most of the operation, on either a temporal or spatial distribution basis, occurs at near the maximum speed. The patterns are close to what one would consider as being ideal, that is, the train can accelerate up to a steady speed and it not restricted by signal stops and the like.

Figure 11.3 shows the temporal distribution and Figure 11.4 shows the spatial distribution. These figures are shown on a large scan in Appendix 8.

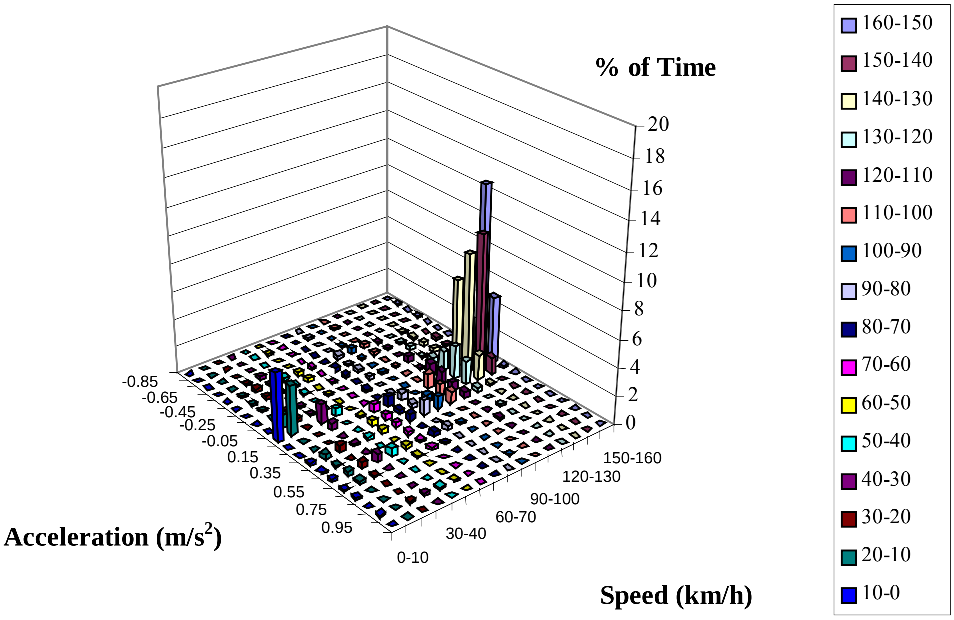


Figure 11.3. Temporal distribution of speeds and accelerations for IC545.

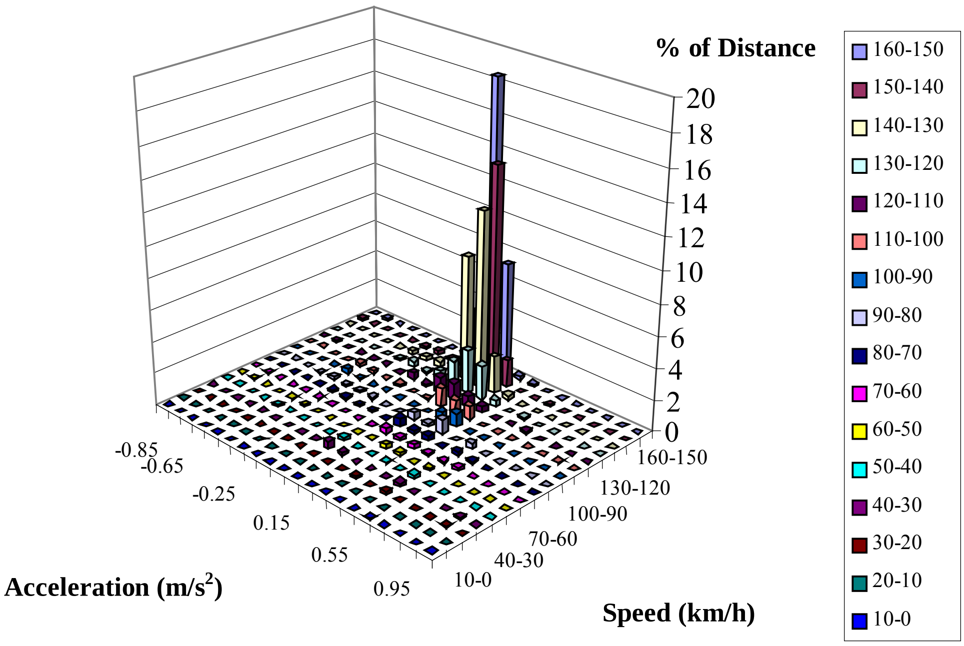


Figure 11.4. Spatial distribution of speeds and accelerations for IC545.

The figures show that the largest portion of the operation (. 33% on a temporal basis and 47% on a spatial basis) takes place at speeds over 140 km/h. The accelerations at this speed lie in the range of $\pm 0{,}35 m/s^2$. This is because the train operates so much of the time with speed above, yet the speed is not truly constant. Some consideration must be given to the definition of "constant" speed operation. That is, under which level of acceleration can the speed be assumed to be approximately constant. The frequencies of speed independent of acceleration and acceleration independent of speed are shown in tables 11.1 and 11.2.

Speeds	**0:50 km/h**	**50:100 km/h**	**100:150 km/h**	**>150 km/h**
Temporal distribution	20	13	49	18
Spatial distribution	3	9	61	27

Table 11.1. Speed interval shares in %

Accelerations (±)	**0 to 0,1 m/s^2**	**0,1 to 0,3 m/s^2**	**Over 0,3 m/s^2**
Temporal distribution	65	20	14
Spatial distribution	73	18	8

Table 11.2. Acceleration interval shares in %.

Figure 11.5 below shows the relationship between the four kinds of operation and a function of both time and distance traveled.

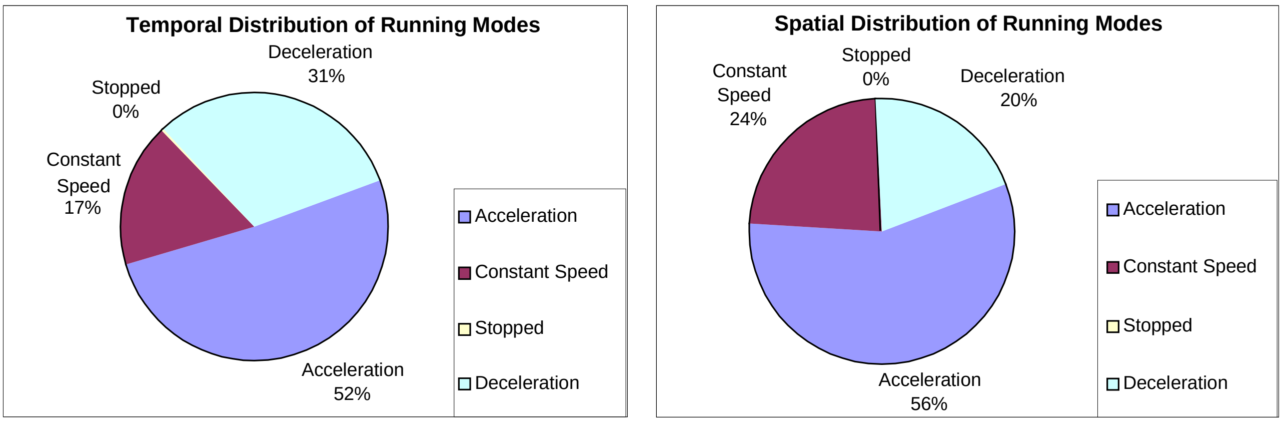


Figure 11.5. Distribution of running modes for IC545

Since the train is an inter city train, stopping does not take up much of the total operating time, and of course on a distance basis, the contribution of stopping is zero. Even on the temporal basis the contribution is close to zero. The biggest difference between the temporal and spatial distributions in the relative amount of deceleration.

11.2 RØ4557 Østerport-Kalundborg

Train speed as a function of both time and distance is shown in figures 11.6 and 11.7.

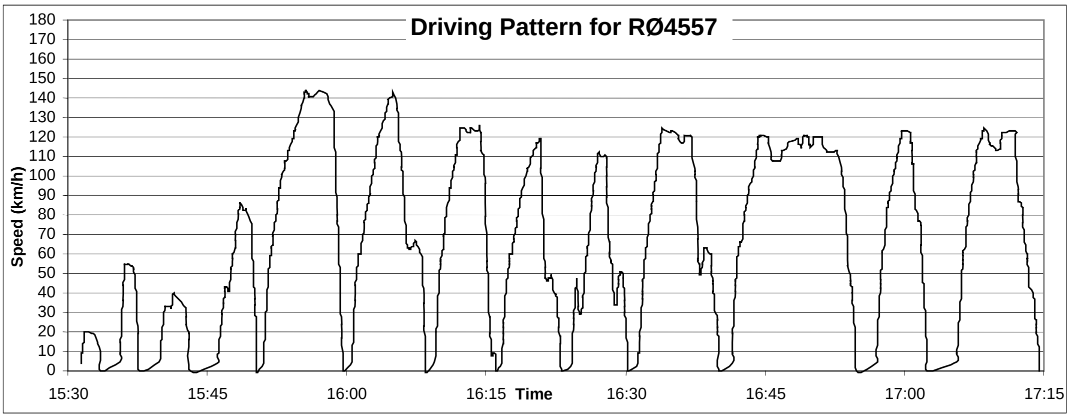


Figure 11.6 Speed as a function of time for a regional train.

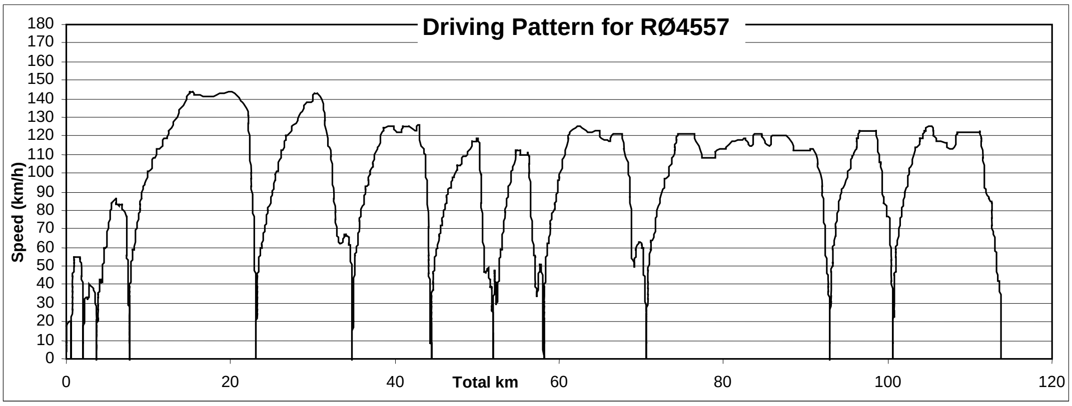


Figure 11.7. Speed as a function of driven km for a regional trains.

Even though this is a regional train, the driving pattern resembles the IC train shown previously. The operation here is relatively conventional, since after every stop the trains can accelerate up to an operating speed, which here is a maximum of about 120 km/h. Between Østerport and Valby, the operation is with relatively low speed, which is due to the short distance between the station, as operation here is in the middle of Copenhagen, and there are many trains. From the speed time curve it can be seen that there is a longer time between different stops. The schedule includes longer stops at the towns of Tølløse og Holbæk near the end of the route.
Figures 11.8 and 11.9 show the distribution of the speed and accelerations. The graphs are shown on a larger scale in Appendix 9.

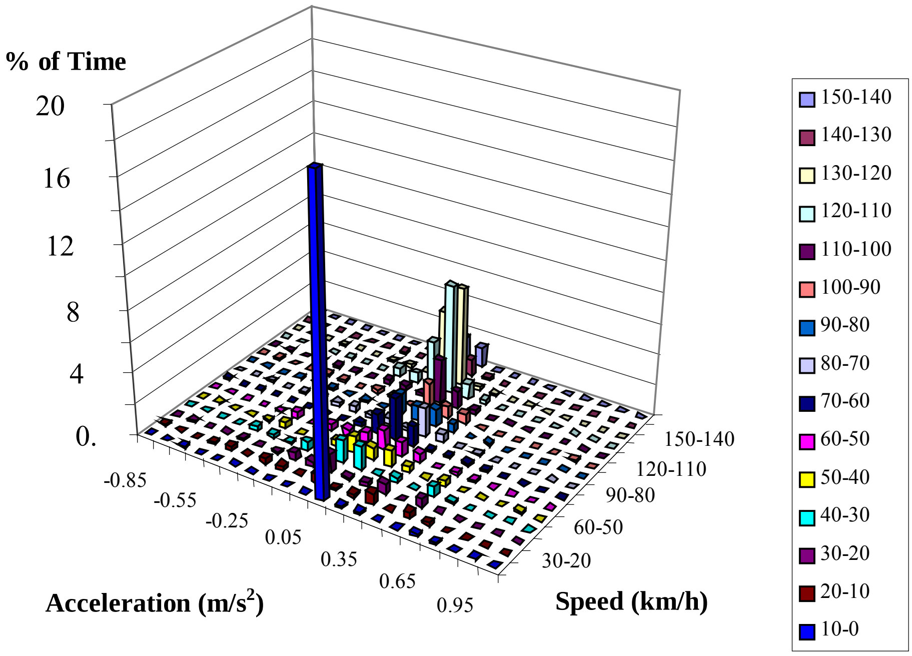


Figure 11.8. Temporal distribution of speeds and accelerations for RØ4557

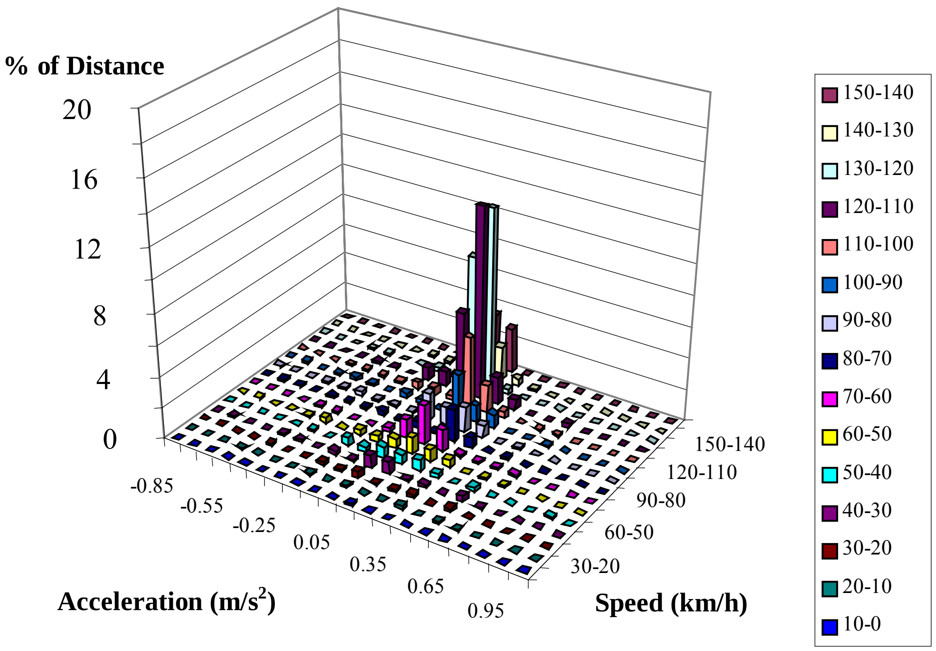


Figure 11.9. Spatial distribution of speeds and accelerations for RØ4557

From both figures, it can be seen that the highest speeds are most common. The most commonly encountered speeds are in between 110 and 140 km/h, these speed ranges having a frequency 54 and 31% for spatial and temporal distributions respectively. There is a greater difference between the spatial and temporal distributions than was the case for the IC train, but like that train, a large portion of the operation is at speeds from 100 km/h up to the maximum speed

One noticeable difference is that for the temporal distribution, 20 of the operation lies in the interval between 0 and 10 km/h and an acceleration of 0-0,1 m/s^2. For the spatial distribution, this share is only 0.14%. For both distributions about 25% of the operation lies between 50 and 100 km/h with accelerations of ±0.3 m/s^2. There is a general tendency that the accelerations, shown in the 3D-graph in figures 11.8 and 11.9 basically do not exceed ±0.3 m/s^2.

Speeds	**0:50 km/h**	**50:100 km/h**	**100:150 km/h**	**>150 km/h**
Temporal distribution	39	25	35	0
Spatial distribution	9	27	63	0

Table 11.3 The distribution of speed intervals in %

Accelerations (±)	**0 to 0,1 m/s^2**	**0,1 to0,3 m/s^2**	**Over 0,3 m/s^2**
Temporal distribution	66	23	10
Spatial distribution	67	24	8

Table 11.4 The distribution of acceleration levels in %

Figure 11.10 shows the distribution of the types of operation. It is seen that the extended stops in schedule have a noticeable influence on the temporal distribution (DSB,1997). The same condition can be seen in Figures 11.8 and 11.9. The train on this route is stopped 20% of the time.

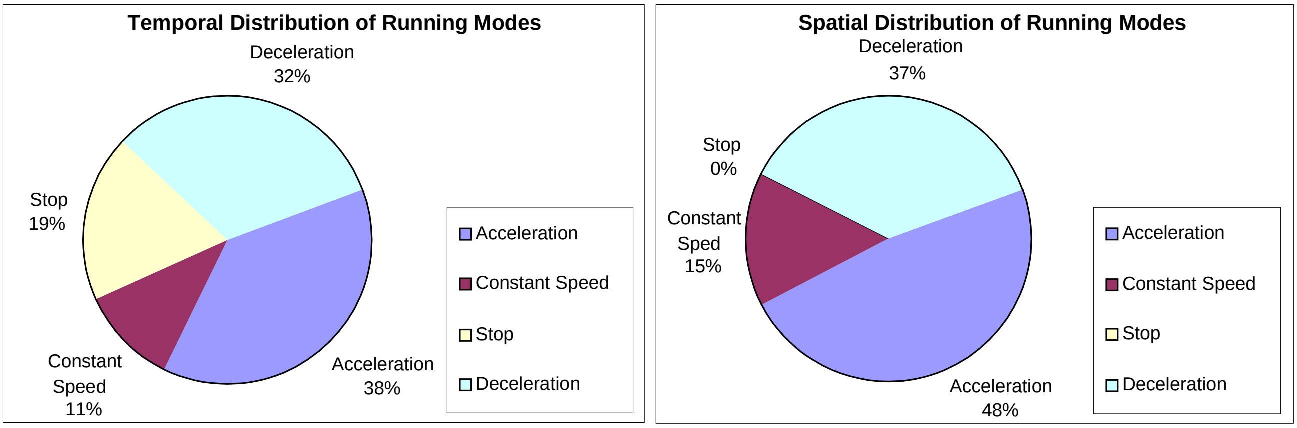


Figure 11.10 Distribution of types of operation for RØ4557.

Deceleration and constant speed operation have about the same percentage in each distribution, when the acceleration portion differs. On about half of the driven km, the train is accelerating, while it is only about 40% of the time that is used for acceleration.

11.3 GP7513 Glostrup-Fredericia

AS an example of a goods train, results for GP7523 are shown. This train was mentioned earlier in connection with the testing and evaluation of the model. The train operates directly between Glostrup and Fredericia and then runs directly to Århus. Since there is no stop underway, with the exception of two signals, the amount of stop time is expected to be quite small. If there were regular stops underway, these would be expected to have a greater percentage than for the passenger trains, since a stop for a goods train usually included switching, brake tests and waiting time until the tracks are free. For even though a goods train operates according to a schedule, it is only advisory. The goods trains usually operate according to how much switching time is needed, and how many goods are to be transported. This can easily give rise to waiting time, since it is necessary to wait for the track to be free.
Even though the train then does not have regular stops, there are many brakings and subsequent accelerations, shown by Figures 11.11 and 11.12. These are traffic related

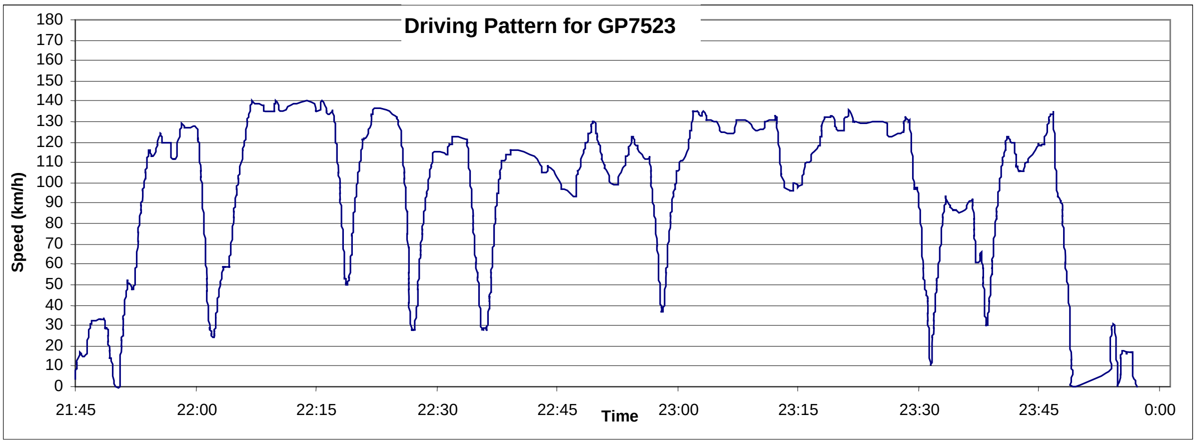


Figure 11.11 Speed as a function of time for GP7523

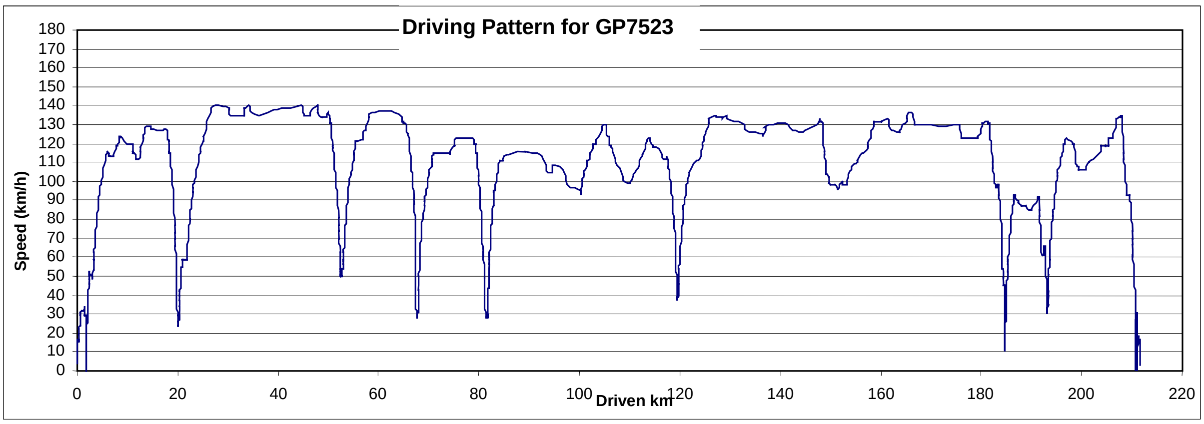


Figure 11.12 Speed as a function of distance for GP7523

The operation is then very uneven, which gives an increase in energy consumption compared to uniform operation. Figures 11.13 and 11.14 show the temporal and spatial distributions of the speeds and accelerations. Larger curves are found in Appendix 10.

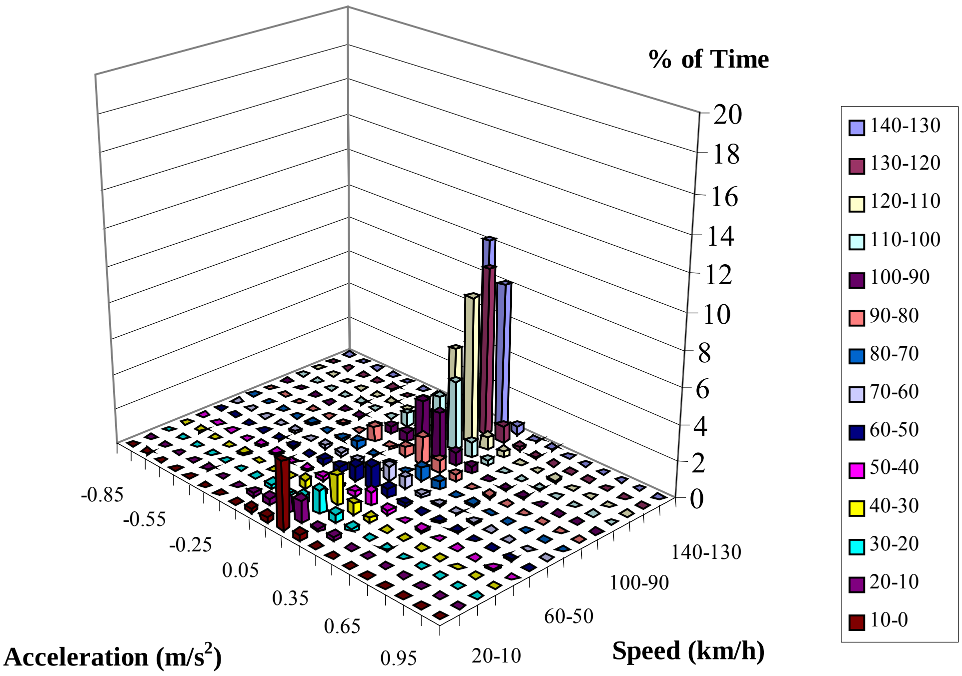


Figure 11.13 Temporal distribution for GP7523.

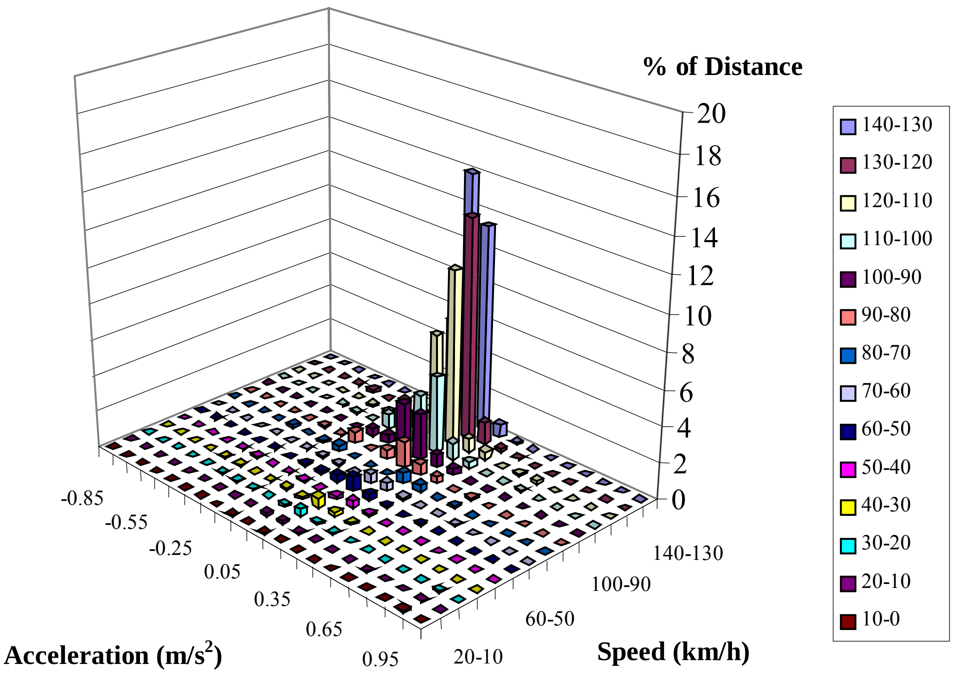


Figure 11.14 Spatial Distribution for GP7523.

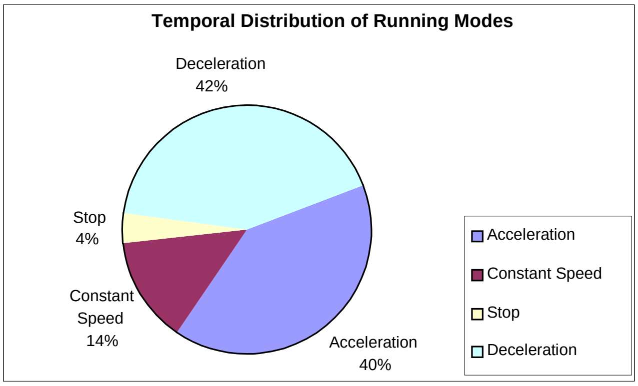
As was seen with the previous trains, most of the operation occurs with the higher speeds. For the temporal and spatial distributions respectively, about 60 and 75% of the operation is in the region 100-140 km/h and ±0,3 m/s^2. Correspondingly about 18% (temporal) and 15% (spatial) of the operation lies in the region between 50 and 100 km/h and acceleration of ±0,3m/s^2. Even the stop time, which occurs because of signaling, takes up about 4% of the total operating time in the form of low speed in connection with the stops. Otherwise the relative amounts of operation are about the same for either time or driven km.

Speeds	**0:50 km/h**	**50:100 km/h**	**100:150 km/h**	**>150 km/h**
Temporal distribution	17	25	61	0
Spatial distribution	4	17	77	0

Table 11.5 Speed interval distribution in %

Accelerations (±)	**0 to 0.1 m/s^2**	**0,1 to 0,3 m/s^2**	**Over 0.3 m/s^2**
Temporal distribution	73	21	4
Spatial distribution	77	17	4

Table 11.6 Distribution of acceleration values in %



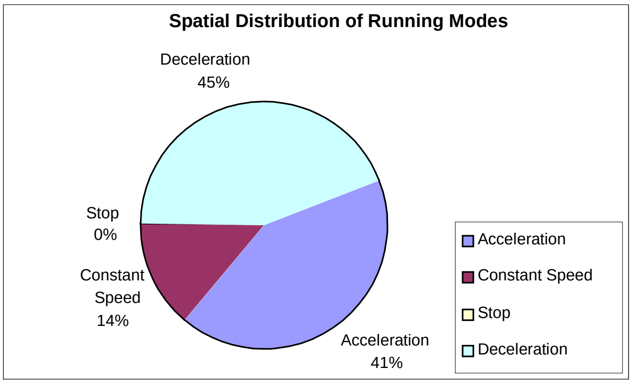


Figure 11.15 Distribution of Running Modes for GP7523.

Acceleration and deceleration each make up about 40% of the operation. This is related to the uneven nature of the operation as shown in Figure 11.11 and 11.12. The many stops and subsequent accelerations, do not allow much time for even operation. This also requires an extra amount of energy.

11.4 GS7499 GB-Århus

To investigate the effect of stops at stations have on goods train operation, a typical goods train is examined. The train, an ordinary goods train, has a route from the Freight yards of Copenhagen (GB) to the town of Århus. It stops along the way in the towns of Ringsted and Fredericia. At other places, switching occurs, and wagons are taken off the train. It left GB with 37 wagons, In Ringsted 11 wagons were taken off, and in Fredericia 13 more wagons removed. A detailed summary of the operation is shown in Table 13e. Since the train changes underway, the energy consumption and emissions were not calculated for the whole trip. On the contrary, they were calculated for each of the three trips, of which the operation in reality consists.

Figures 11.16 and 11.17 show the operating pattern

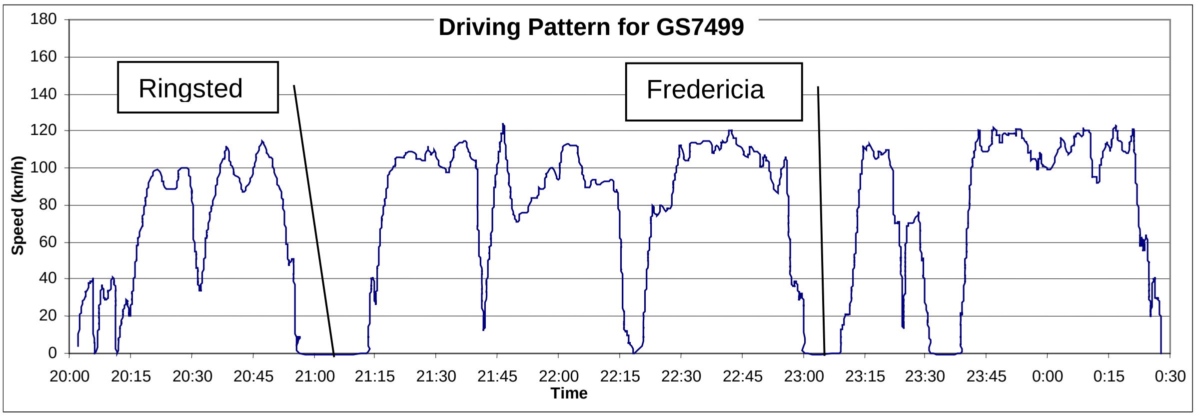


Figure 11.16 Speed as a function of time for GS7499

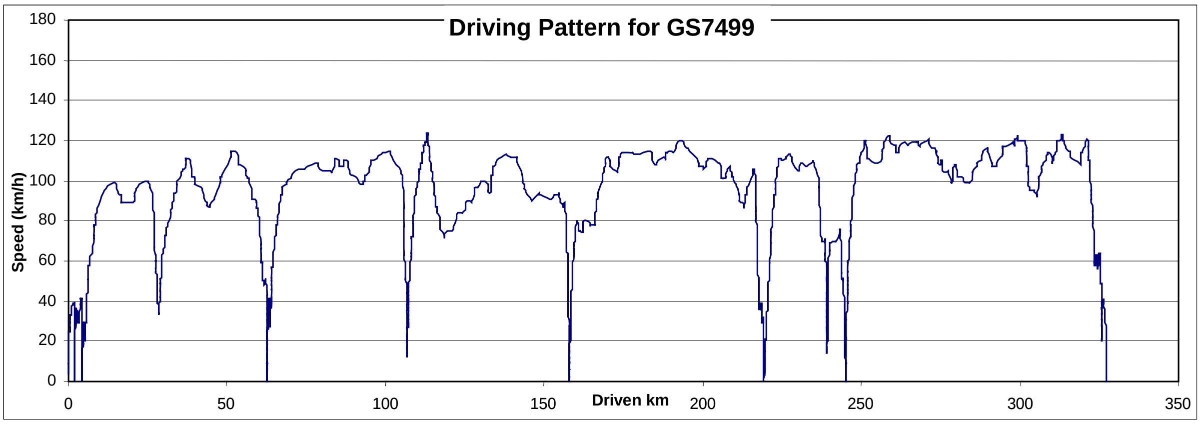


Figure 11.17. Speed as a function of distance for GS7499

The figures show that the operation, like that of GP7523 is irregular as compared to the passenger trains. Though the number of brakings is not as large as for GP7523. There are two stops along the way in addition to Ringsted and Fredericia. The train stops in

Odense (between Ringsted and Frederica) and Vejle (after Fredericia), which apparently is due to signals or passing. The normal speed for unencumbered operation is between 100 and 120 km/h. The irregular operation is because the train is relatively heavy. Between GB and Ringsted the weight is 973 tons. Between Ringsted and Fredericia 716 tons and on the last stretch to Århus the train weight is about 416 tons.

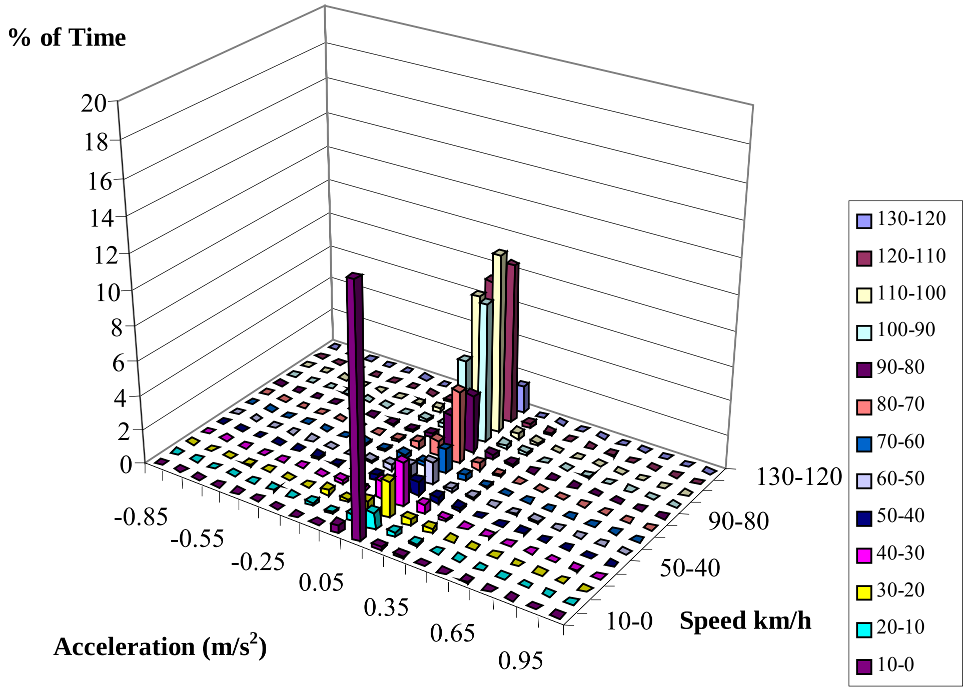


Figure 11.18 Temporal distribution for GS7499

Figures 11.18 and 11.19 show the distribution of the acceleration and speed intervals.

Like the previous train, most of the operation occurs at speeds over 100 km/h. And correspondingly, most of the acceleration spectrum (98%) for both distribution lies between ± 0.3 m/s^2. As much as 60% temporally and 56% spatially lie between accelerations of 0 and 0.1 m/s^2, which can be seen by the few columns in the figures. For the temporal distribution the stop times have a large influence on the results, and constitute as much as 14%, also seen in the diagrams of Figure 11.20.

Speeds	**0:50 km/h**	**50:100 km/h**	**100:150 km/h**	**>150 km/h**
Temporal distribution	29	31	40	0
Spatial distribution	6	35	59	0

Table 11.7 Distribution of speeds in %.

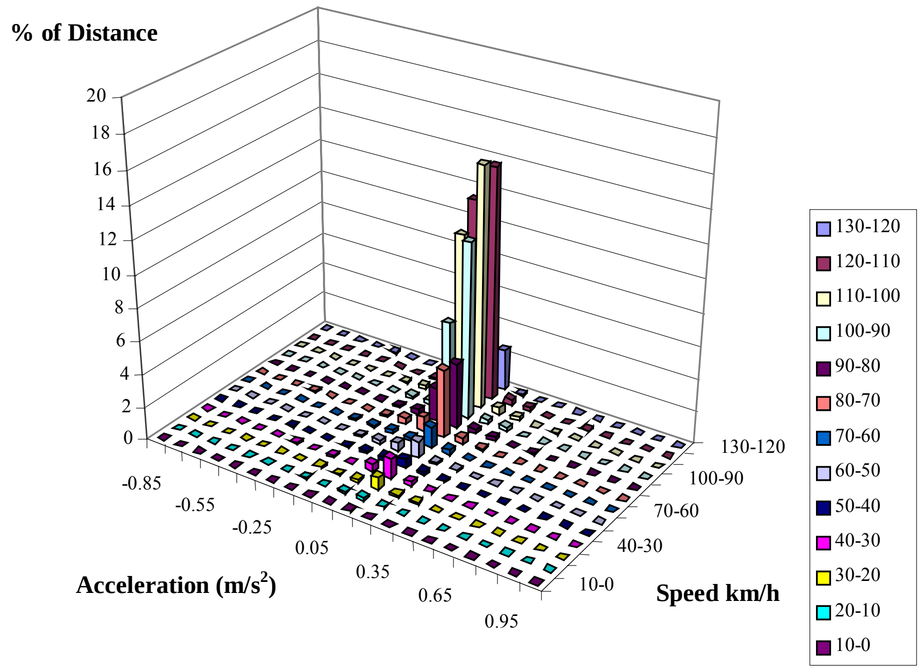


Figure 11.19 Spatial distribution for GS7499

Accelerations (±)	**0 to 0.1 m/s^2**	**0.1 til 0.3 m/s^2**	**Over 0.3 m/s^2**
Temporal distribution	88	10	2
Spatial distribution	90	9	1

Table 11.8 Distribution of acceleration levels in %.

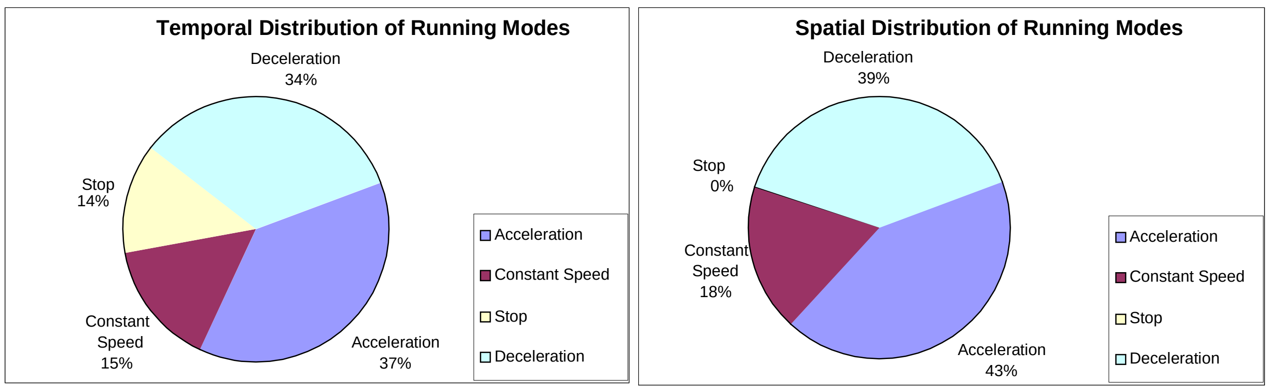


Figure 11.20 Distributions of Running Modes for GS7499

With reference to the driving pattern in figures 11.16 and 11.17, a large portion of the operation occurs with braking/coasting and acceleration. 15 temporally and 18% spatially of the operation occurs with constant speed. On a temporal basis, the percent of time for acceleration is 37% and for deceleration 34%, nearly the same. For the spatial distribution, things are similar, except that the stop time does not appear. The acceleration here makes up 43%, of the operation, deceleration almost 40%.

11.5 Summary.

The operation of three different types of trains has been examined.

The InterCity train operates most of the time at speeds between 100 and 150 km/h. Most of the acceleration is low, that is between –0,1 and 0,1 m/s^2.

The regional train operation is mainly also over 100 km/h, though to a lesser degree than the IC train. There is a greater range of accelerations. About 25% of the trains' accelerations are between ±0.1 and ±0.3.m/s^2. Basically all the rest lie between –0,1 and 0,1 m/s^2.

For post (goods) train that does not have scheduled intermediate stops, the speed are mainly in the intervals above 50 km/h. Acceleration levels are closest to those of the IC-train. About 75 % of the accelerations are between –0.1 and 0.1 m/s^2.

The common goods train has a more uniform distribution of speeds over all levels, though the most frequent speeds are between 50 and 120 km/h. The accelerations are mainly distributed with the interval –0,1 to 0,1 m/s^2. This is due to the many stops and the high weight of the train.

12 Simulation of Operating Parameters

In this section, the model previously described will be used to evaluate the effect of several operating parameters on energy consumption and emissions. The following three parameters will be investigated:

- Number of stops
- Uniformity of operation
- Maximum speed.

The results will be used to illustrate different driving patterns and their effect on energy consumption.
First, the effect of the number of stops on consumption and emissions will be investigated. In other words, what does it cost to allow a train that operates over a given stretch to stop a varying number of times?
Then the effect of the "quality" of the operation on energy consumption will be illustrated. The train can be operated in different ways given the same stop requirements and speed limits, depending on the conditions of the signals, the technique of the engineer and traffic limitations of the tracks.

12.1 Analysis of number of stops

In order to make this analysis, the coastal passenger route from Copenhagne mina station (København H) to Elsinore (Helsingør) is used. This route is heavily used by commuters in the area north of Copenhagen. Even though modern equipment is used on the route, the travel time is basically the same as it was 40 years ago. This is partly due to the problem that the route is short in relation to the number of station. The length of the route is only 46 k, and there are 14 stations, including the end stations. This gives an average of about 3,5 km between the individual stations, though the stations in Copenhagen itself are closer together than those outside the city. A large amount of the operation consists of acceleration and deceleration/braking.

In the following, three scenarios will be looked at, all of which are based on actual train operating profiles.

The scenarios are:

- Normal regional trains. Stops at all stations.
- Rush Hour train. Does not stop between Kokkedal and Østerport. (passes 4 outer suburban stations in a row)
- Express trina (InterNord). No stops between Helsingør og København H.

The simulations are made using a distribution of operating conditions. In order to ensure that the distributions are relevant, they are bases on actual driving patterns and then simplified. This was done to ensure that the operating patterns are within the limits imposed by the locomotive power and the infrastructure.

The driving patterns selected were chosen such that there were no abnormal stops, signal stops, or unusual operation in general.

Table 12.1 shows the overall data for the trains on which the analysis is based. More detailed data is shown in the overview in Appendix 12. Only one direction is shown for the sake of simplicity, that is the direction from Helsingør to København H.

Category	Train used	No. wagons	Total tons weight	No. of seats	Stops	Elapsed time	Average speed
Normal train	RØ3063	6	340,5	440	12	62 min.	44,7 km/h
Rush hour train	RØ3061	6	340,5	440	7	48 min.	57,8 km/h
Express	IN 392 (24/2 99)	7	431	520	0	35 min.	79,2 km/h

Table 12.1 Over all data for the driving patterns used to obtain operating distributions

As expected, the trip time is very dependent of the number of stops underway. The stops nearly double the trip time.

12.1.1 Operating distribution

The operating state distributions were entered into the model, when then calculated the energy consumption and emissions. It was assumed that the emissions and energy consumption during deceleration were not significant, that is, there is no type of regenerative braking. The distributions were based on the time, and not the distance traveled. Three speed intervals were used. Since the trains have different maximum speeds, the intervals were adjusted to accommodate the maximum speed of the train in question.

Operation of a normal train:

Figure 12.1 shows the operating state distribution for this type of train. All distributions are shown on a larger scale in Appendix 12.

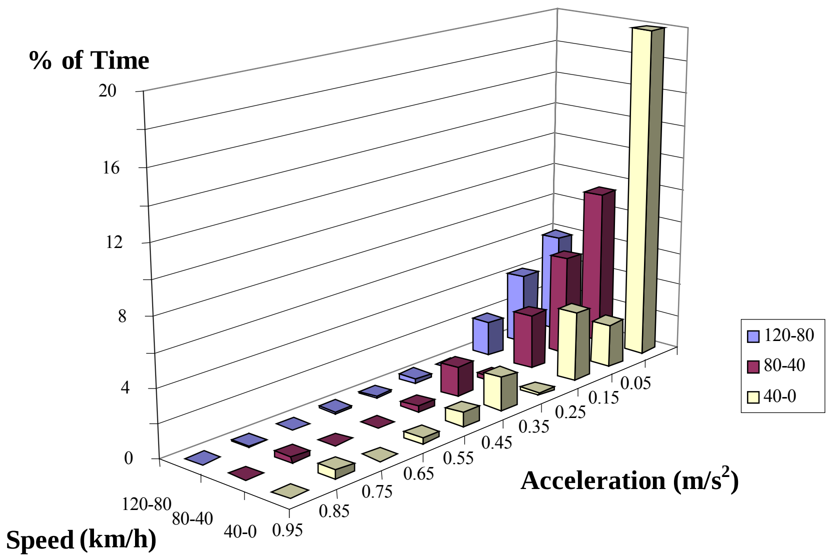


Figure 12.1 Spatial distribution of the speed and accelerations for a regional with stops at all stations

The figure shows that a large portion of the operating pattern consists of a stopped train. This is, of course due to all the station. The distribution shows the highest frequency of operation in the lowest third of the velocity scale.

Speeds	0:40 km/h	40:80 km/h	80:120 km/h
Temporal Distribution	37	22	13
Spatial Distribution	8	30	28

Table 12.2 Distribution of speeds - %

The spatial distribution looks a little different, because the stop time is not represented the same here.
The distribution for the accelerations intervals are shown in Table 12.3:

Accelerations	0 to 0.1 m/s^2	0.1 to 0.3 m/s^2	Over 0.3 m/s^2
Temporal Distribution	42	22	7
Spatial Distribution	27	30	8

Table 12.3. Distribution of acceleration intervals - %

Operation of a rush hour train:

Figure 12.2 shows the corresponding distribution of operating states for the rush hour train that does not stop between Kokkedal and Østerport.

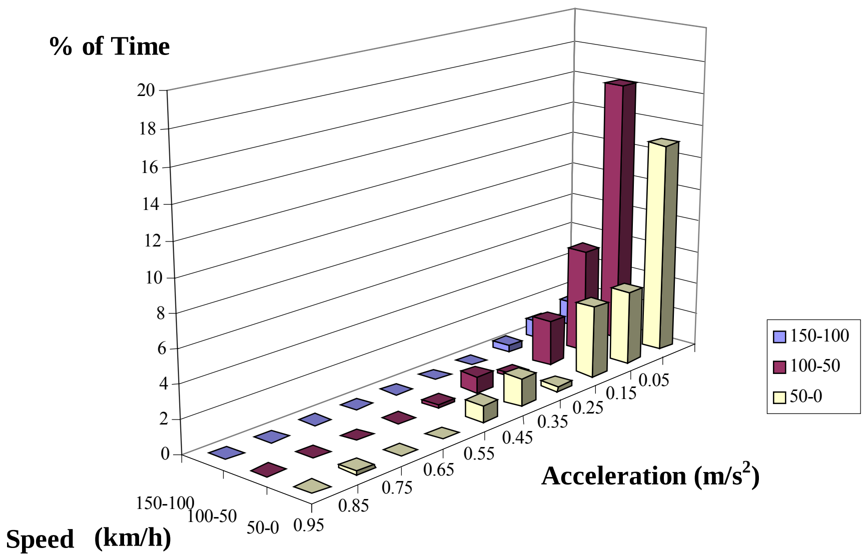


Figure 12.2 Temporal distribution of speeds and accelerations for the rush hour train.

For the temporal distribution the percent of time for the stopped condition is smaller than the standard train. Relative to a train that stops at all stations, the portion of time for stopping is smaller due to the smaller number of stops. However, the train operates less at the highest speeds, that is, from 100 to 150 km/h.

Speeds	0:50 km/h	50:100 km/h	100:150 km/h
Temporal Distribution	25	27	3
Spatial Distribution	8	30	28

Table 12.4 Distribution of speeds - %

Accelerations	0 to 0.1 m/s^2	0,1 to 0.3 m/s^2	Over 0.3 m/s^2
Temporal Distribution	31	20	5
Spatial Distribution	27	20	4

Table 12.5 Distribution of acceleration intervals - %

It can be seen that the total percent of accelerations is much lower than for the local train. Here the sum of acceleration percents was 71 and 65%, respectively, while the corresponding values for the rush hour train were 56 and 51%, again a result of fewer stops. The fewer the stops, the better the chances for covering the stretch with nearly constant speed.

<u>Through train.</u>

For the international train that has no intermediate stops, the temporal distribution is shown in figure 12.3:

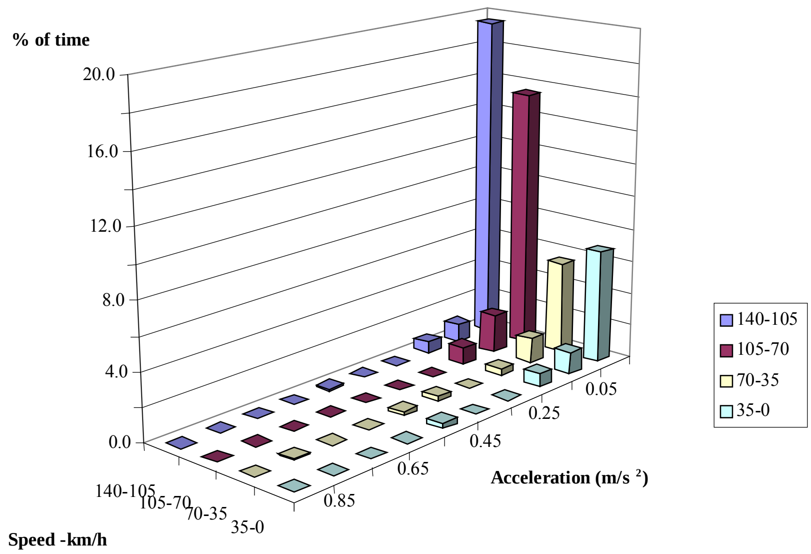


Figure 12.3 Temporal distribution for through train.

A drastically different picture is seen here, as compared to the regional trains. The operation is basically in the area above 70 km/h. This is because the train does not stop, but also because there is adequate capacity such that the train's speed is not restricted.

Speeds	0:35 km/h	35:70 km/h	70-105km/h	105:140 km/h
Temporal Distribution	9	8	19	21
Spatial Distribution	3	5	20	30

Table 12.6 Distribution of speeds - %

Accelerations	0 to 0,1 m/s^2	0,1 to 0,3 m/s^2	Over 0,3 m/s^2
Temporal Distribution	47	7	1
Spatial Distribution	49	5	0

Table 12.7 Distribution of acceleration intervals - %

It can also be seen that the train does not have high rates of acceleration. Most of them are in the area of 0 to 0,1 m/s^2, which corresponds to a single acceleration in connection with departure from Helsingør. After this, the speed is nearly constant.

12.1.2 Energy Consumption

The energy consumption is described in the following. The following table shows the energy consumption as well as the CO_2 and NO_x emissions calculated on the basis of spatial and temporal distributions of driving conditions.

$E(x_{\%})$	kJ/ton km	kJ/seat km	CO_2 g/ton km	CO_2 g/seat km	NO_x g/ton km	NO_x g/seat km
Normal train	456,1	389,5	33,96	28,99	0,60	0,51
Rush hour train	290.21	247.8	21.75	18.57	0.39	0.33
Through train	188.79	171.58	14.05	12.77	0.25	0.23

Table 12.8 Energy consumption based on spatial distribution - $E(x_{\%})$

$E(t_{\%})$	kJ/ton km	kJ/seat km	CO_2 g/ton km	CO_2 g/seat km	NO_x g/ton km	NO_x g/seat km
Normal train	417.57	356.55	31.08	26.54	0.55	0.47
Rush hour train	333.97	285.16	26.15	22.33	0.46	0.40
Through train	194.92	177.16	14.51	13.19	0.26	0.23

Table 12.9 Energy consumption based on temporal distribution - $E(t_{\%})$

The results in these tables show that there is a very large difference in the energy consumption and the emissions. From the calculations based on the spatial distribution, the rush hour train uses only about 44% of the energy that the normal regional train uses on the same trip. The spatial distribution based calculation gives a corresponding reduction of 50%. Since average emissions factors are used, the differences in emissions are the same.

The through train uses only between 64 and 80% of the energy used by the other train types. That is, reducing the number of stops gives a large reduction in the energy consumption. A combination of some through trains and those that stop at all stations is expected to reduce energy consumption and emissions for this route.

12.2 Analysis of driving patterns

A second example of the use of the model is shown in the following, where the influence of driving behavior on energy consumption is shown for a given route. The same IC-train operation as before is investigated, with the same stop pattern and the same speed limit. Two patterns are compared, one where there are no disturbances and the second over the same route, where disturbances arise. The differences are shown for the first part of the route, from Copenhagen Main to Høje Tåstrup. The purpose is to illustrate the "quality" of the driving.

The particular stretch of track considered is one of the busier in the Danish system, and is a prime candidate for expansion. Because of capacity limits, trains are often slowed in respect to the scheduled operation.

Category	**Train/date:**	**Train sets**	**Total weight**	**Total Seats**	**Elapsed time**	**Trip speed**
Normal operation	IC129 d 5/1 99	3	291	432	11,5 min.	100,2 km/h
Abnormal operation	IC129 d 7/1 99	3	291	432	13 min	88,8 km/h

Table 12.10 Train operating data.

Both IC-trains operate with 3 IC3-sets (MF). The maximum speed is about 140 km/h for both trains.

12.2.1 Driving patterns

Figure 12.4 shows the measured speed distance histories for the operation of these two trains between Copenhagen Main and Høje Tåstrup.

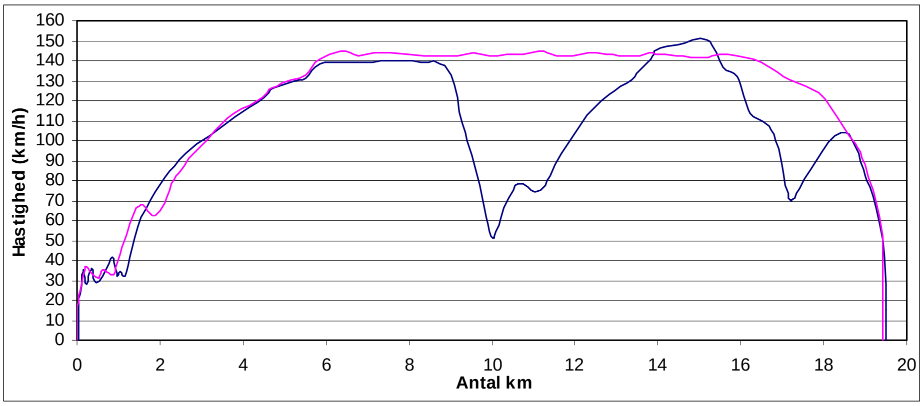


Figure 12.4 Speed distance histories for the normal and abnormal operation of an Inter City train between Copenhagen Main and Høje Tåstrup.

The operations are nearly the same for the first 8 km, but in the abnormal operation two sharp braking periods occur in the last 10 km. There are no stops other than the scheduled stop at Høje Tåstrup. The acceleration velocity distributions for the two driving patterns are shown in Figures 12.5 and 12.6 and on a larger scale in Appendix. 13.

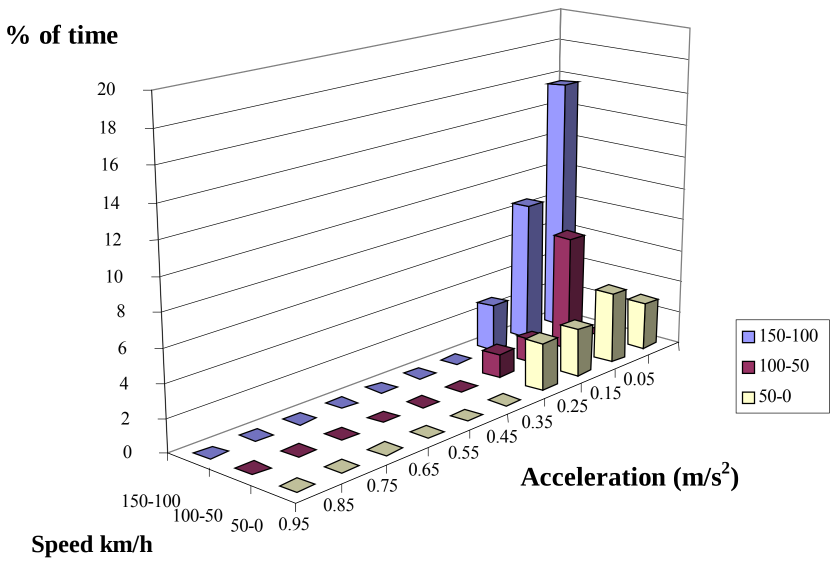


Figure 12.5 Temporal acceleration speed distribution for the normal operation.

Most of the normal operation occurs between 100 and 150 km/h, which is due to the fact that the normal operation requires only a single acceleration at the departure.

Speeds	0:50 km/h	50:100 km/h	100-150 km/h
Temporal Distribution	13	10	27
Spatial Distribution	3	8	37

Table 12.11. Distribution of train speeds in %

Accelerations	0 to 0,1 m/s^2	0,1 to 0,3 m/s^2	Over 0,3 m/s^2
Temporal Distribution	19	17	4
Spatial Distribution	24	21	2

Table 12.12. Distribution of train accelerations in %

The acceleration values are relatively low. Even though the train must come up to a speed of 140 km/h, the accelerations are primarily in the area of up to 0,3 m/s^2.

The distribution for the abnormal operation is shown in Figure 12.6. It can be seen that there is a significant change in the distribution. There is a higher frequency of lower speeds than for the normal operation, due to the braking. As expected from the speed distance profile, speeds in the range 50 to 100 km/h are much more prevalent.

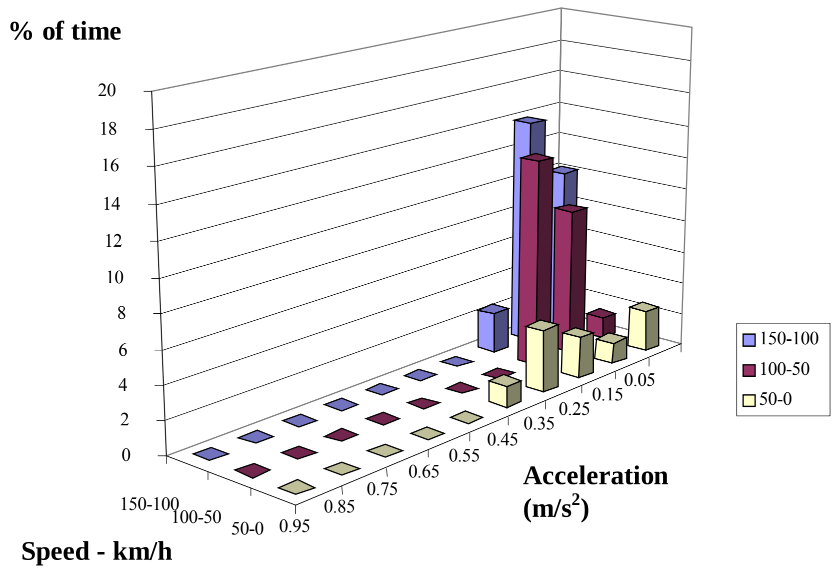


Figure 12.6 Temporal distribution for uneven operation.

Speeds	0:50 km/h	50:100 km/h	100-150 km/h
Temporal Distribution	11	23	27
Spatial Distribution	13	10	27

Table 12.13 Speed distributions in %

Accelerations	0 to 0,1 m/s^2	0,1 to 0,3 m/s^2	Over 0,3 m/s^2
Temporal Distribution	14	42	5
Spatial Distribution	19	27	4

Table 12.14 Acceleration distribution in %

Correspondingly, the accelerations levels change in the middle interval, that is, in the area between 0,1 to 0,3 m/s^2, where previously there was a large concentration at the lower levels. In all, this means a more uneven operation with a lower average speed, with more accelerations of a longer duration.

12.2.2 Energy Consumption

The tables below show the results from the simulations. The energy consumption is calculated from both the temporal and spatial distributions.

$E(x_{\%})$	kJ/ton km	kJ/seat km	CO_2 g/ton km	CO_2 g/seat km	NO_x g/ton km	NO_x g/seat km
Normal operation	205.47	154.84	15.29	11.53	0.27	0.20
Ueaven operation	325.84	245.56	24.26	18.28	0.43	0.32

Table 12.15 Energy consumption and emissions from spatial distribution.

$E(t_{\%})$	kJ/ton km	kJ/seat km	CO_2 g/ton km	CO_2 g/seat km	NO_x g/ton km	NO_x g/seat km
Normal operation	250	189	18.6	14.1	0.33	0.25
Uneven operation	354	267	26.4	19.9	0.47	0.35

Table 12.16 Energy consumption and emissions from temporal distribution.

For $E(x_{\%})$ the difference for consumption and emissions are 63%, while the corresponding difference for $E(t_{\%})$ is 71%.
That is to say, the uneven operation uses 60 and 40% more energy respectively than the even operation. Problems with stops, speed reductions, and limited capacity cause an increase in energy consumption of about 50%.

Only two operations are simulated, so there is a limited base of comparison, but one could conceive of a worse situation for the uneven operation. It is assumed that the limited operation would be somewhat typical, and not representative of a situation with a large number of stops over such a short distance.

Of course, most operations are longer than this, and it would be expected that the above results would be averaged with a longer stretch of more typical operation, where giving smaller differences.

12.3 Analysis of maximum speed

In extension of the analysis of the effect of the irregularity of the train operation with regard to the energy consumption, this chapter investigates the effect of maximum speed on the energy consumption and emissions of selected trains.
Three IC trains are investigated, which operate between Copenhagen and Korsør. They stop underway in Høje Tåstrup, Roskilde, Ringsted and Slagelse. The operation patterns are for scheduled operation, without any unintended stops or slowdowns.
These three trains operate with maximum speeds of 140, 160 and 180 km/h

respectively. Selected data relative to the trains and their operation is shown in Table 12.17.

Category	Train nr:	Train Sets	Total Weight	Number of Seats	Stops	Elapsed time	Average speed
140	IC129 d 5/1 99	3	291	432	4	61,2 min.	106,1km/h
160	IC129 d 8/1 99	3	291	432	4	56,3 min	115,4 km/h
180	IC133 d 8/1 99	3	291	432	4	54,2 min.	119,8 km/h

Table 12.17 Train operating data.

Even though there is a relatively large difference in the average speeds, this translates into a time difference of only about seven minutes between the fastest and slowest train.

12.3.1 Operation profiles

The speed distance profiles for the three operations are shown in figure 12.7.

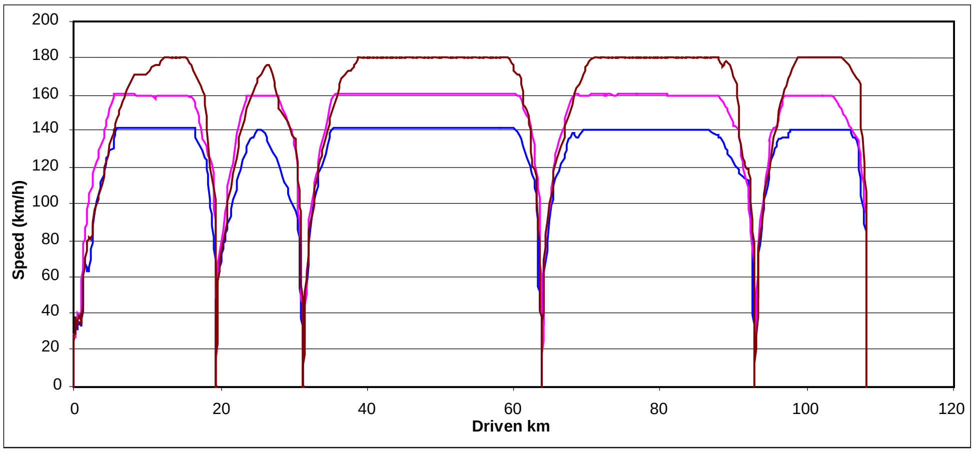


Figure 12.7 Speed as a function of distance driven for the three operations of Table 12.17.

The accelerations are mostly of about the same magnitude for all operations, though with some few deviations. Numbers for the distributions and larger graphs are given in Appendix 14. Figures 12.8, 12.9 and 12.10 are the temporal distributions for maximum speeds of 140, 160 and 180 km/h respectively. Three speed intervals are shown for each operation, normalized to the maximum speed, so the intervals have slightly different values.

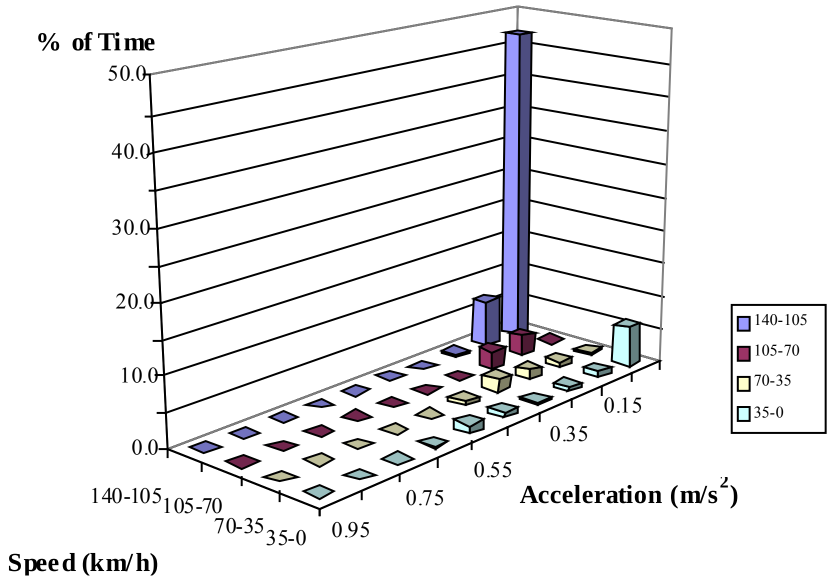


Figure 12.8 Temporal distribution for operation with max. speed of 140 km/h.

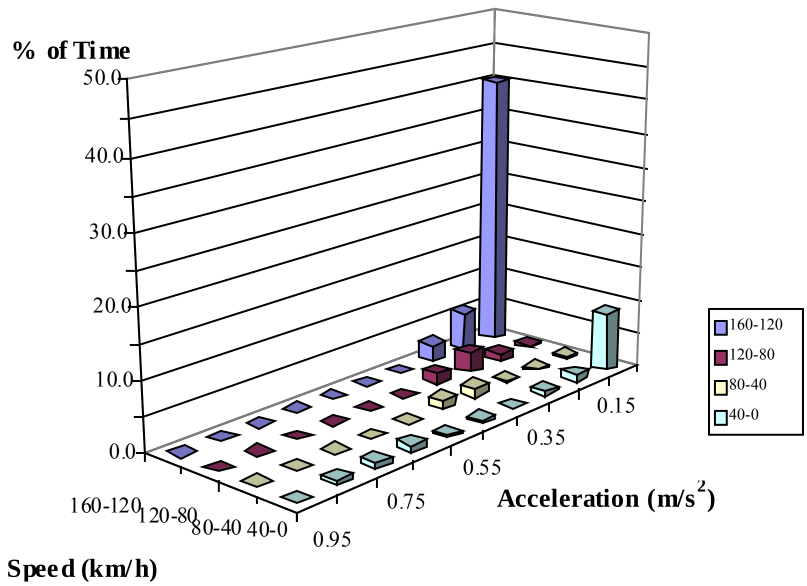


Figure 12.9 Temporal distribution for operation with max. speed of 160 km/h.

t

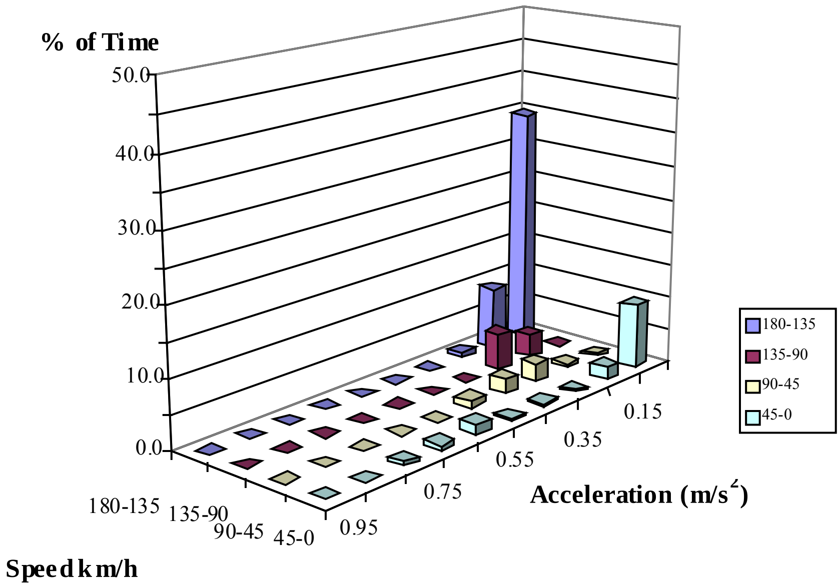


Figure 12.10 Temporal distribution for operation with max. speed of 180 km/h.

The operation distributions shown in the above figures are very similar, in spite of the difference in the value of the top speed and the intervals. The values are shown in the tables below.

Speeds	**0:35 km/h**	**35:70 km/h**	**70-105 km/h**	**105-140 km/h**
Temporal Distribution	10	5	4	54
Spatial Distribution	1	3	5	70

Table 12.18 Speed interval shares in % for v_{max} = 140 km/h.

Accelerations	**0 to 0,1 m/s²**	**0,1 to 0,3 m/s²**	**Over 0,3 m/s²**
Temporal Distribution	53	16	5
Spatial Distribution	62	14	2

Table 12.19 Acceleration interval shares in % for v_{max} = 140 km/h.

Speeds	**0:40 km/h**	**40:80 km/h**	**80-120 km/h**	**120-160 km/h**
Temporal Distribution	13	4	6	48
Spatial Distribution	1	2	5	64

Table 12.20 Speed interval shares in % for v_{max} = 160 km/h

Accelerations	0 to 0,1 m/s^2	0,1 to 0,3 m/s^2	Over 0,3 m/s^2
Temporal Distribution	49	14	7
Spatial Distribution	55	14	4

Table 12.21 Acceleration interval shares in % for ν_{max} = 160 km/h.

Speeds	0:45 km/h	45:90 km/h	90-135 km/h	135-180 km/h
Temporal Distribution	15	7	9	45
Spatial Distribution	1	4	8	63

Table 12.22 Speed interval shares in % for ν_{max} = 180 km/h.

Accelerations	0 to 0,1 m/s^2	0,1 to 0,3 m/s^2	Over 0,3 m/s^2
Temporal Distribution	45	24	7
Spatial Distribution	50	24	3

Table 12.23 Acceleration interval shares in % for ν_{max} = 180 km/h.

In other words, the driving pattern has basically the same distribution for all three operations. That is, operation is mostly at low accelerations and higher speeds. The lowest half of the acceleration scale is hardly represented in any of the operations with the exception of stops at the stations.

12.3.2 Energy Consumption.

In tables 12.24 and 12.25 below, the results of the simulations are given. In both cases it is advantageous to lower the speed to lower the energy consumption.

$E(x_{\%})$	kJ/ton km	kJ/seat km	CO_2 g/ton km	CO_2 g/seat km	NO_x g/ton km	NO_x g/seat km
140 km/h	272.01	204.99	20.25	15.26	0.36	0.27
160 km/h	298.60	225.03	22.23	16.75	0.39	0.30
180 km/h	345.19	260.14	25.70	19.36	0.46	0.34

Table 12.24 Effect of maximum speed on energy consumption for IC train, spatial distribution.

For the spatial distribution, it is possible to save about 14% by lower the top speed by 20 km/h. A further reduction of 40 km/h, that is to 140 km/h, give a reduction of 22%.

As expected, the calculations using the temporal distribution are almost the same. Here, the saving with the reduction of the top speed is about 10%. For a maximum speed of 140 km/h, the corresponding reduction is about 20%.

$E(t_{\%})$	kJ/ton km	kJ/seat km	CO_2 g/ton km	CO_2 g/seat km	NO_x g/ton km	NO_x g/seat km
140 km/h	299.95	226.05	22.33	16.83	0.40	0.30
160 km/h	337.12	254.06	25.10	18.91	0.45	0.34
180 km/h	374.07	281.90	27.85	20.98	0.49	0.37

Table 12.25 Effect of maximum speed on energy consumption for IC train, temporal distribution.

Though there is a considerable energy savings, it is at the cost of added travel time. Reducing the maximum speed to 140 km/h increases the travel time by about 7 minutes (see Table 12.17). In addition to lower customer satisfaction, this would reduce capacity, since the train spends more time on the lines.

12.4 Summary

Simulations were performed to analyze three factors of operation: Number of stops, the evenness of the operation and the maximum speed. In all cases, significant savings in energy consumption and emissions are achievable. By using trains that stop at a selected number of stations, simulations indicate a saving for the commuter trains on the coastline of about 35%.

Uneven operation has also unfortunate consequences for the energy consumption and emissions. In the simulation of short trip operation between Copenhagen and Høje Tåstrup, the energy consumption for steady operation with no stop was about half of that with the irregular operation.

A minor reduction in maximum speed gave lower, but significant reductions in energy consumption and emissions. A speed reduction from 180 to 160 km/hfor operation between Copenhagen H and Korsør (about 110 km) gave a reduction on the order of 10-14%.

13 Trends for Energy Consumption

In addition to simulation of certain problem formulations, in this section the model is used in a broader perspective.

As written earlier in the report, the energy consumption and emissions for a train depend on many parameters and factors. Some of these factors are: Maximum and average speed, total weight, loaded weight, tare weight, number of axles and the amount of passengers or goods. In the following, the effect of several of these parameters on energy consumption will be described. In the current model formulation, emissions are directly proportional to energy consumption. This has been shown to be a very good assumption for CO2, NOx, SOx, and to a lesser degree the other emissions.

A substantial amount of data has been made available from DSB for the project. This data, which includes crash logs, train data and technical data, have been used to analyze energy consumption and emissions from different train types. The types of trains are described in Chapter 2. The object is to use a number of simulated operations to describe operating patters and show the relation between the characteristics of trains and energy consumption and emissions.

The results have been calculated using printout of crash log data. All calculations were made on the basis of spatial distributions. Normally, diesel and electrical consumption are show separately. Since the number of electrical trains in this report is limited, the consumption of electrical trains will be shown together with the diesel powered trains.

The operating patterns used are shown in tables 13.1, 13.2, 13.3, 13.4 and 13.5.
The following translates the less obvious Danish terms in the headings.
Dato = Date
Tognr = train number
Fra = from
Til = to
Togsæt = train set
Tara = tare
Total Vægt = total wieght
Længde = length
Start tid = start time
Slut tid = end time
Antal vogne = number of wagons

Dato	Tognr	Fra	Til	Km	Togsæt	Antal togsæt	Tara	Total vægt	passagerer	Længde	Start tid	Slut tid	C_L	C_R
5/1 99	IC125	Kh	Ar	328.9	-	3	291	325.56	432	176.4	08:00	11:12	1.47	1.72E-03
6/1 99	IC125	Kh	Ar	328.8	-	3	291	325.56	432	176.4	08:00	11:08	1.47	1.72E-03
7/1 99	IC125	Kh	Ar	328.9	-	3	291	325.56	432	176.4	07:59	11:09	1.47	1.72E-03
5/1 99	IC129	Kh	Ar	328.9	-	3	291	325.56	432	176.4	09:00	12:10	1.47	1.72E-03
6/1 99	IC129	Kh	Ar	328.9	-	3	291	325.56	432	176.4	09:00	12:40	1.47	1.72E-03
7/1 99	IC129	Kh	Ar	328.9	-	3	291	325.56	432	176.4	09:00	12:11	1.47	1.72E-03
8/1 99	IC129	Kh	Ar	328.9	-	3	291	325.56	432	176.4	09:02	12:15	1.47	1.72E-03
4/1 99	IC133	Kh	Ar	328.8	-	3	291	325.56	432	176.4	10:01	13:07	1.47	1.72E-03
5/1 99	IC133	Kh	Ar	327.7	-	3	291	325.56	432	176.4	10:02	13:12	1.47	1.72E-03
6/1 99	IC133	Kh	Ar	328.8	-	3	291	325.56	432	176.4	09:59	13:08	1.47	1.72E-03
7/1 99	IC133	Kh	Ar	328.9	-	3	291	325.56	432	176.4	10:02	13:08	1.47	1.72E-03
8/1 99	IC133	Kh	Ar	328.9	-	3	291	325.56	432	176.4	10:04	13:37	1.47	1.72E-03
4/1 99	IC137	Kh	Ar	328.9	-	3	291	325.56	432	176.4	11:00	14:09	1.47	1.72E-03
5/1 99	IC-Lyn 23	Kh	Ar	328.9	-	3	291	325.56	432	176.4	07:51	10:30	1.47	1.72E-03
6/1 99	IC-Lyn 23	Kh	Ar	328.9	-	3	291	325.56	432	176.4	07:51	10:55	1.47	1.72E-03
7/1 99	IC-Lyn 23	Kh	Ar	328.9	-	3	291	325.56	432	176.4	07:51	10:39	1.47	1.72E-03
5/1 99	IC128	Ar	Kh	327.2	-	3	291	325.56	432	176.4	11:05	14:20	1.47	1.72E-03
6/1 99	IC128	Ar	Kh	329.0	-	3	291	325.56	432	176.4	11:02	14:19	1.47	1.72E-03
7/1 99	IC128	Ar	Kh	328.8	-	3	291	325.56	432	176.4	11:03	14:15	1.47	1.72E-03
5/1 99	IC132	Ar	Kh	328.8	-	3	291	325.56	432	176.4	12:02	15:17	1.47	1.72E-03
6/1 99	IC132	Ar	Kh	328.8	-	3	291	325.56	432	176.4	12:02	15:16	1.47	1.72E-03
7/1 99	IC132	Ar	Kh	328.8	-	3	291	325.56	432	176.4	12:03	15:18	1.47	1.72E-03
5/1 99	IC136	Ar	Kh	327.5	-	3	291	325.56	432	176.4	13:06	16:20	1.47	1.72E-03
6/1 99	IC136	Ar	Kh	328.8	-	3	291	325.56	432	176.4	13:05	16:25	1.47	1.72E-03
7/1 99	IC136	Ar	Kh	326.2	-	3	291	325.56	432	176.4	13:06	16:16	1.47	1.72E-03
8/1 99	IC136	Ar	Kh	328.7	-	3	291	325.56	432	176.4	13:05	16:17	1.47	1.72E-03
4/1 99	IC-Lyn 40	Ar	Kh	327.7	-	3	291	325.56	432	176.4	13:42	16:27	1.47	1.72E-03
5/1 99	IC-Lyn 40	Ar	Kh	329.0	-	3	291	325.56	432	176.4	13:39	16:25	1.47	1.72E-03
6/1 99	IC-Lyn 40	Ar	Kh	329.0	-	3	291	325.56	432	176.4	13:40	16:29	1.47	1.72E-03
7/1 99	IC-Lyn 40	Ar	Kh	328.9	-	3	291	325.56	432	176.4	13:41	16:24	1.47	1.72E-03
8/1 99	IC-Lyn 40	Ar	Kh	328.9	-	3	291	325.56	432	176.4	13:39	16:26	1.47	1.72E-03
4/1 99	IC-Lyn 42	Ar	Kh	328.7	-	3	291	325.56	432	176.4	14:39	17:26	1.47	1.72E-03

Table 13.1 Operations with MF (IC and IC-Lyn)

Dato	Tognr	Fra	Til	Km	Togsæt	Antal togsæt	Tara	Total vægt	passagerer	Længde	Start tid	Slut tid	C_L	C_R
4/10 99	IC917	Kh	Od	160.5	ER2043	2	266	302.8	460	153.06	06:32	08:01	1.31	2.69E-03
4/10 99	IC908	Od	Kh	160.5	ER2043	1	133	151.4	230	76.53	08:16	09:48	0.8	1.65E-03
4/10 99	IC545	Kh	Od	160.5	ER2043	1	133	151.4	230	76.53	13:33	15:03	0.8	1.65E-03
5/10 99	IC190	Fa	Kh	220.6	ER2043	1	133	151.4	230	76.53	03:53	06:07	0.8	1.65E-03
5/10 99	IC917	Kh	Od	160.5	ER2043	2	266	302.8	460	153.06	06:31	08:04	1.31	2.69E-03
5/10 99	IC917	Od	Sø	196.8	ER2043	1	133	151.4	230	76.53	08:06	10:12	0.8	1.65E-03
5/10 99	IC924	Sø	Kh	357.1	ER2043	1	133	151.4	230	76.53	11:01	15:09	0.8	1.65E-03
5/10 99	IC957	Kk	Od	166.19	ER2043	2	266	302.8	460	153.06	16:19	18:01	1.31	2.69E-03
5/10 99	IC957	Od	Sø	196.8	ER2043	1	133	151.4	230	76.53	18:05	20:13	0.8	1.65E-03
6/10 99	IC537	Kh	Od	160.5	ER2043	2	266	302.8	460	153.06	11:31	13:01	1.31	2.69E-03
6/10 99	IC528	Od	Kh	160.5	ER2043	2	266	302.8	460	153.06	14:16	15:49	1.31	2.69E-03
4/10 99	Re	Od	Fr	60.3	ER2043	1	133	151.4	230	76.53	15:35	16:31	0.8	1.65E-03
4/10 99	Re	Fr	Od	60.3	ER2043	1	133	151.4	230	76.53	16:43	17:40	0.8	1.65E-03
4/10/99	Re	Od	Fr	60.3	ER2043	1	133	151.4	230	76.53	18:35	19:32	0.8	1.65E-03

Table 13.2 Operations with ER (IC and Re)

Dato	Tognr	Fra	Til	Km	Lokomotiv	Antal vogne	Tara (vogne)	Tara lok	Total taravægt	Passagerer	Længde	Start tid	Slut tid	C_L	C_R
24/2 99	IN392	Kh	Hg	45.75	MZ1457	7	308	123	431	520	220	22:05	22:40	1.870	2.39E-03
25/2 99	IN 392	Kh	Hg	45.76	MZ1457	11	484	123	607	840	280	22:05	22:40	2.310	2.17E-03
26/3 99	RØ3061	Hg	Kh	46.01	MZ1458	6	217.5	123	340.5	440	170	16:09	16:57	1.76	2.83E-03
25/3 99	RØ4557	Kk	Kb	113.81	MZ1458	8	289.5	123	412.5	600	220	15.32	17.15	1.98	2.46E-03
24/1 99	RØ4287	KK	Næ	90.53	ME1514	4	145.5	115	260.5	280	120	22:54	24:05	1.540	2.96E-03
25/1 99	RØ4219	KK	Nf	148.10	ME1514	4	145.5	115	260.5	280	120	6:51	8:47	1.540	2.96E-03
23/3 99	RØ2269	Kk	Nf	149.64	MZ1458	6	253.5	123	376.5	440	170	18.54	20.55	1.76	2.57E-03
31/1 99	RØ1529	Kh	Kb	110.20	MZ1458	5	181.5	123	304.5	360	150	08.40	10.15	1.65	2.80E-03
31/1 99	RØ2216	Næ	Kk	95.00	Me1508	4	145.5	115	260.5	280	120	10:03	11:20	1.540	2.96E-03
31/1 99	RØ2225	Kk	Næ	97.00	Me1508	4	145.5	115	260.5	280	120	7:54	9:10	1.540	2.96E-03
25/1 99	RØ4280	Næ	Kk	97.39	ME1514	4	145.5	115	260.5	280	120	0:12	1:24	1.540	2.96E-03
25/1 99	RØ2260	Nf	Kk	185.53	ME1514	6	217.5	115	332.5	440	170	20:18	22:13	1.76	2.57E-03
2/2/99	RØ4238	Næ	Kk	94.67	ME1508	4	145.5	115	260.5	280	120	10:12	11:24	1.540	2.96E-03
2/2/99	RØ4239	Kk	Næ	94.57	ME1508	4	145.5	115	260.5	280	120	11:54	13:05	1.540	2.96E-03
2/2/99	RØ2252	Nf	Kk	151.09	ME1508	6	217.5	115	332.5	440	170	18:18	20:20	1.76	2.57E-03
1/31/99	RØ2241	Kk	Nf	153.99	ME1508	4	145.5	115	260.5	280	120	11:54	13:55	1.540	2.96E-03
25/9 99	RØ5577	Kk	Kb	114.00	MZ1458	3	109.5	123	232.5	200	100	20:14	22:09	1.43	2.98E-03
25/9 99	RØ5568	Kb	Kk	113.00	MZ1458	3	109.5	123	232.5	200	100	22:53	0:50	1.43	2.98E-03
24/5 99	RØ3072	Kh	Hg	46.15	MZ1457	7	253.5	123	376.5	520	200	16:41	17:29	1.87	2.51E-03
25/4 99	RØ3072	Kh	Hg	46.15	MZ1457	7	253.5	123	376.5	520	200	16:41	17:29	1.87	2.51E-03
4/12 99	Rø3062	Kh	Hg	46.06	Mz1456	6	217.5	123	340.5	440	170	09:12	10:07	1.76	2.57E-03
4/12 99	Rø3063	Hg	Kh	46.05	Mz1456	6	217.5	123	340.5	440	170	10:54	11:56	1.76	2.57E-03

Table 13.3 Operations with locomotive powered passenger trains, MZ4 and ME. (RØ)

Dato	Tognr	Fra	Til	Km	Togsæt	Antal vogne	Tara	Total taravægt	assagere	Længde	Start tid	Slut tid	C_L	C_R
24/6 99	3856	Ti	Ar	278.4	MR 4041	1 sæt	69	79.6	132	44.68	12:59	15:45	0.967	1.83E-03
24/6 99	3521	Ar	Al	140.4	MR 4041	1 sæt	69	79.6	132	44.68	17:44	18:23	0.967	1.83E-03
25/6 99	5293	Al	Fh	84.9	MR 4041	1 sæt	69	79.6	132	44.68	04:56	06:27	0.967	1.83E-03
25/6 99	5226	Fh	Al	85.0	MR 4041	1 sæt	69	79.6	132	44.68	06:52	08:10	0.967	1.83E-03
23/6 99	5249	Al	Fh	84.7	MR 4090	1 sæt	69	79.6	132	44.68	18:46	19:55	0.967	1.83E-03
24/6 99	5209	Ab	Fh	84.7	MR 4090	1 sæt	69	79.6	132	44.68	08:46	09:55	0.967	1.83E-03
24/6 99	5252	Fh	Ab	84.7	MR 4090	1 sæt	69	79.6	132	44.68	14:17	15:24	0.967	1.83E-03
24/6 99	5268	Fh	Ab	84.1	MR 4090	1 sæt	69	79.6	132	44.68	17:21	18:29	0.967	1.83E-03
23/6 99	3917	Ar	Hr	93.8	MR 4090	1 sæt	69	79.6	132	44.68	07:52	09:22	0.967	1.83E-03
27/6 99	3880	Str	Ar	148.0	MR 4044	1 sæt	69	79.6	132	44.68	21:41	23:51	0.967	1.83E-03
28/6 99	3506	Gr	Ar	69.0	MR 4044	1 sæt	69	79.6	132	44.68	05:00	06:23	0.967	1.83E-03
29/6 99	3912	Sl	Ar	53.0	MR 4044	1 sæt	69	79.6	132	44.68	06:24	07:09	0.967	1.83E-03
22/6 99	3134	Ar	Fr	106.4	MR 4053	1 sæt	69	79.6	132	44.68	11:19	12:30	0.967	1.83E-03
22/6 99	3145	Kd	Ar	126.0	MR 4053	1 sæt	69	79.6	132	44.68	13:17	14:53	0.967	1.83E-03
22/6 99	3447	Ar	Str	216.3	MR 4053	1 sæt	69	79.6	132	44.68	15:22	18:39	0.967	1.83E-03
18/6 99	3647	Fr	Eb	86.5	MR 4053	1 sæt	69	79.6	132	44.68	14:36	15:47	0.967	1.83E-03
23/6 99	3820	Str	Ar	145.1	MR 4053	1 sæt	69	79.6	132	44.68	05:42	7:10	0.967	1.83E-03
21/6 99	3864	Str	Ar	145.1	MR 4053	1 sæt	69	79.6	132	44.68	04:42	18:10	0.967	1.83E-03
22/6 99	4339	Fr	Kd	19.4	MR 4053	1 sæt	69	79.6	132	44.68	12:46	13:02	0.967	1.83E-03
21/6 99	4605	Eb	Str	143.5	MR 4053	3 sæt	207	238.7	396	134	05:00	05:19	1.567	2.00E-03

Table 13.4 Operations with MR. (RV)

Dato	Tognr	Fra	Til	Km	Lokomotiv	Antal vogne	Godsvægt	Belastningsvægt	Tara, vogne	Tara, lok	Total vægt	Længde	C_L	C_R
7/10 99	GS7499	Gb	Rg	62.64	Me1506	37	296	858.88	562.88	115	973.88	540	6	2.58E-03
7/10 99	GS7499	Rg	Fa	26.845	Me1506	26	208	602.88	394.88	115	717.88	390	10	3.05E-03
7/10 99	GS7499	Fa	Ar	55.465	Me1506	13	104	300.19	196.19	115	415.19	210	5.2	3.17E-03
28/9 99	Gs7495	Gb	Rg	63.87	Me1534	21	168	491.06	323.06	115	606.06	320	6	2.54E-03
28/9 99	Gs7495	Rg	Fa	156.25	Me1534	29	232	676.38	444.38	115	791.38	430	6	2.89E-03
28/9 99	Gs7495	Fa	Ar	106.45	Me1534	19	152	440.25	288.25	115	555.25	290	6	3.40E-03
15/9 99	GS7495	Gb	Rg	63.87	Me1503	21	168	486.44	318.44	115	601.44	320	12	3.51E-03
15/9 99	GS7495	Rg	Fa	156.25	Me1503	25	224	646.38	422.38	115	761.38	420	10	2.78E-03
15/9 99	GS7495	Fa	Ar	106.45	Me1503	18	144	415.56	271.56	115	530.56	280	4.5	3.38E-03
4/5 99	GP7523	Gl	Fa	211	Me1505	7	126	314	188	115	429	190	2.15	3.14E-03
4/5 99	GP7523	Fa	Ar	108	Me1505	6	126	285	159	115	400	160	2.00	3.02E-03
4/5 99	GP7523	Ar	Tov	9.5	Me1505	3	126	205.5	79.5	115	320.5	100	1.55	2.28E-03
26/1 99	GP7516	Tov	Fa	115	Me1535	2	36	90	54	115	205	70	1.40	4.09E-03
26/1 99	GP7516	Fa	Gl	211	Me1535	8	144	358	214	115	473	210	2.30	3.07E-03
3/2 99	GP7506	Od	Gl	148.5	Me1521	4	72	291	219	115	406	120	1.70	3.19E-03
20/9 99	GP7504	Ar	Fa	108.46	Me1515	6	108	268.77	160.77	115	383.77	160	2	3.41E-03
20/9 99	GP7504	Fa	Rg	156.675	Me1515	5	90	223.97	133.97	115	338.97	140	1.85	3.56E-03
20/9 99	GP7504	Rg	Gl	54.77	Me1515	4	72	179.19	107.19	115	294.19	120	1.7	3.33E-03
28/9 99	GP7504	Ar	Fa	108.425	Me1534	6	108	268.77	160.77	115	383.77	160	2	3.41E-03
28/9 99	GP7504	Fa	Rg	156.465	Me1534	5	90	223.97	133.97	115	338.97	140	1.85	3.56E-03
28/9 99	GP7504	Rg	Gl	52.535	Me1534	4	72	179.19	107.19	115	294.19	120	1.7	3.33E-03
10/5 99	GP7502	Fa	Od	60	Me1505	10	180	448	268	115	563	260	2.60	2.85E-03
7/5 99	GP7502	Fa	Sg	156	Me1510	10	180	448	268	115	563	260	2.60	2.90E-03
7/5 99	GP7502	Sg	Gl	56.5	Me1510	7	180	448	185.5	115	480.5	190	2.15	2.17E-03
25/1 98	GP7501	Gl	Od	148.7	Me1535	6	0	314	314	115	429	190	2.00	3.05E-03
25/1 99	GP7501	Od	Ar	168.5	Me1535	7	0	358	314	115	429	210	2.15	3.07E-03
27/1 99	GP7291	Rg	Od	95.8	Me1535	12	160	457	297	115	572	310	2.90	2.97E-03
5/10 99	GP 7502	Tov	Fa	115	Me1506	6	108	268.78	160.78	115	383.78	160	2	3.06E-03
5/10 99	GP 7502	Fa	Rg	156.465	Me1506	10	180	447.94	267.94	115	562.94	260	4.3	2.85E-03
5/10 99	GP 7502	Rg	Gl	52.535	Me1506	8	144	358.38	214.38	115	473.38	210	3	2.54E-03
24/3 99	G9521	GB	Kb	108	MZ1458	8	0	229	229	123	352	150	4.70	3.07E-03
26/3 99	G9521	GB	Kb	108	MZ1458	11	130	416	286	123	539	170	4.70	2.68E-03
1/3 99	G9464	Kj	Gb	51.92	MZ1457	-	161	886	725	123	1009	660	6.7	1.90E-03
25/2 99	G9425	Gb	Kj	53	Mz1457	36	878	1316.36	438.36	123	1439.36	490	7.4	2.10E-03
25/1 99	G9409	Gb	Kj	52.5	Me1508	25	1358	1928	570	115	2043	520	7.50	1.58E-03
13/9 99	G9217	Gb	Rg	64	Me1508	25	399.1	914.43	515.33	115	1029.43	500	12	2.18E-03
13/9 99	G9217	Rg	Næ	55.885	Me1508	29	215.4	691.85	476.45	115	806.85	500	5.2	2.95E-03
13/9 99	G9217	Næ	Nf	26.815	Me1508	3	21	71.79	50.79	115	186.79	80	1.7	3.70E-03
20/9 99	G9217	Gb	Rg	62.64	Me1515	39	357.6	1087.24	729.64	115	1202.24	560	10	2.83E-03
20/9 99	G9217	Rg	Næ	26.845	Me1515	29	254.8	824.07	569.27	115	939.07	520	11.8	2.97E-03
20/9 99	G9217	Næ	Nf	55.465	Me1515	7	59.5	177.39	117.89	115	292.39	160	4.5	3.26E-03
27/1 99	G89106	Od	Rg	96	Me1535	14	112	315.59	203.59	115	430.59	220	6	3.11E-03
27/1 99	G89106	Rg	GB	62	Me1535	12	96	274.88	178.88	115	389.88	190	6	2.84E-03
8/2 99	G7515	Ar	Ab	142.345	Me1522	1	18	44.8	26.8	115	159.8	50	1.25	3.93E-03

Table 13.5 Operations with goods trains, MZ4 and ME. (GP, GS and G)

13.1 Goods train

For goods trains, the energy consumption is shown as a function of the total weight as well as the amount of goods. In Figure 13.1 the energy consumption is shown per ton km. An exponential function is used to show the trend line.

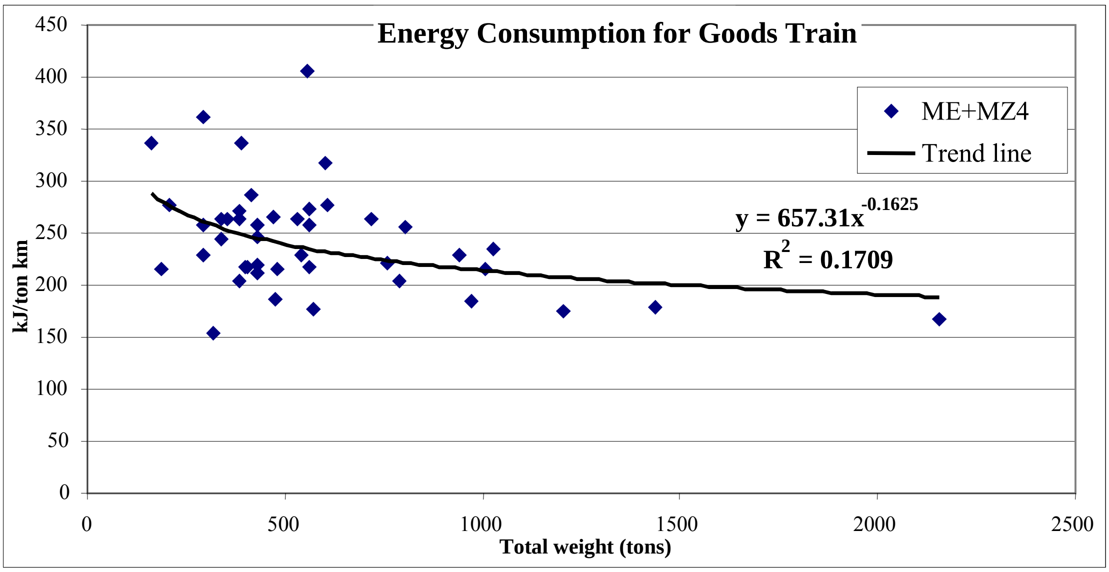


Figure 13.1 Energy consumption for a goods train as a function of the total weight in tons.

Due to a significant scatter in the results for the smaller goods trains, the trend line does not fit the data very well for trains under 600 tons. The spread is up to 100 kJ/ton km corresponding to 40%. For goods trains 600 tons the function describes the results to within about 15%. The energy consumption per goods ton as a function of the amount of goods is shown in figure 13.2.

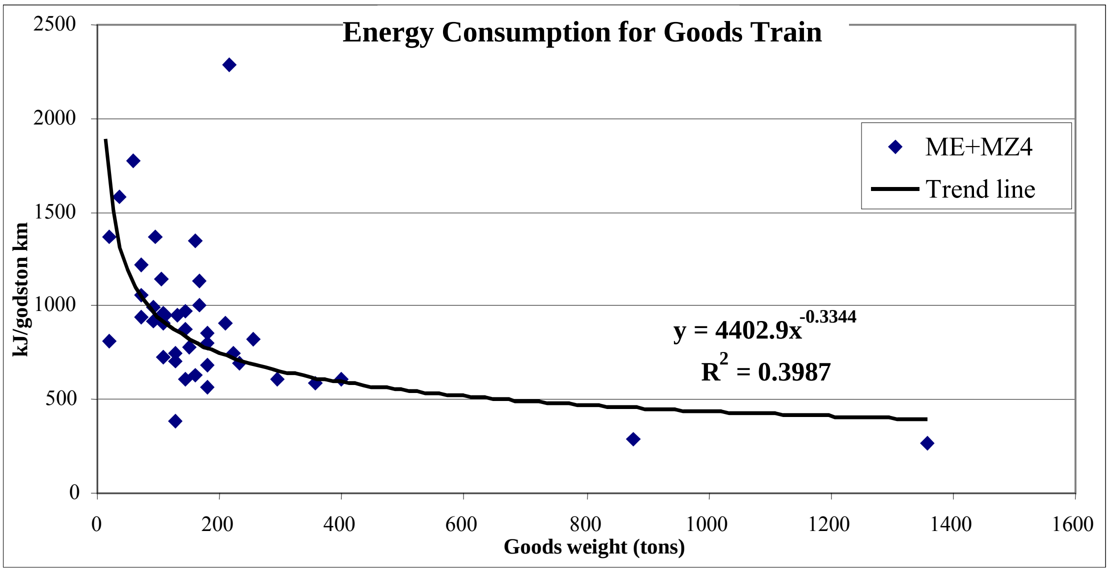


Figure 13.2 Energy consumption per goods ton-km as a function of amount of goods.

The trend line fits better in this case, but the energy consumption increases sharply at light loads, when the goods weight becomes a smaller fraction of the total train weight. That is to say, the load factor is very important here.

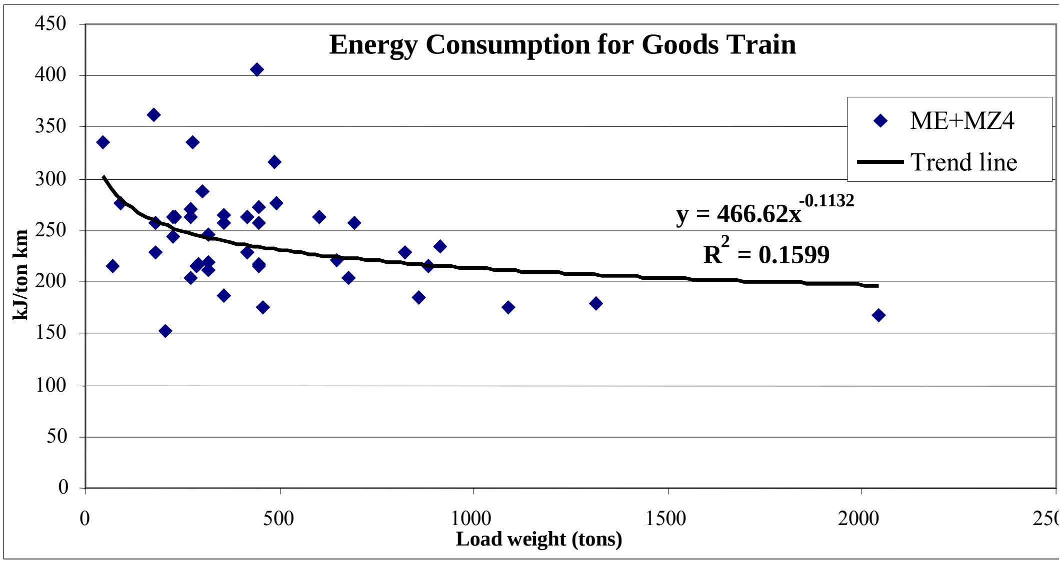


Figure 13.3 Energy consumption for a goods train (less locomotive).

Figure 13.3 shows the same results, but this time as a function of the load at the coupler, that is the total train weight less the weight of the locomotive.

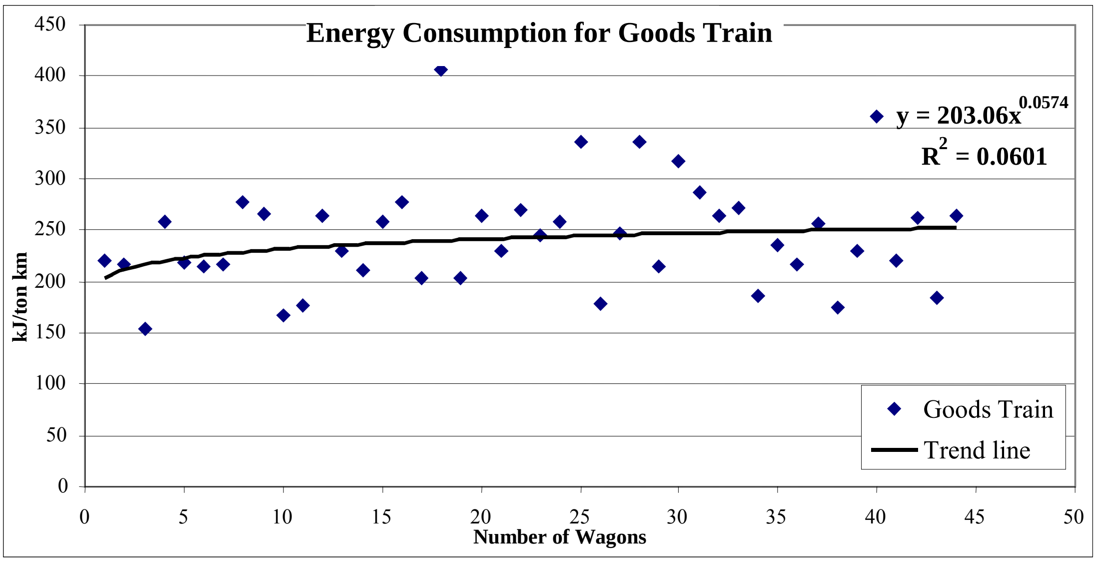


Figure 13.4 Energy consumption per ton km as a function of number of wagons for a goods train.

This gives a picture of the actual size of the train, that is, wagons and goods, since the locomotive is not included. The small trains become more apparent here. The data for the smallest train sized is still quite scattered, and thus the trend line cannot really represent the data for the small trains. This gives a picture of the actual size and utilization of the train, since the locomotives are not included.

Figure 13.4 shows energy consumption per ton-km as a function of the number wagons for goods trains. The highest energy consumption on this basis is for a train with 18 wagons, but as previous figures show, this train only has a goods weight of about 200 tons. Thus load factor is plays a significant factor in determining the energy consumption, especially on the basis of amount of goods transported.

Emissions figures are not shown, since they are proportional to energy consumption when average fuel specific emissions factors are used.

For comparison purposes, Appendix 15, shows corresponding curves from the TRENDS (Georgakaki, et. al., 2002).

13.2 Passenger Trains

In contrast to goods trains, passenger trains are more homogeneous, with respect to material type and size. Therefore, it is of limited value to show energy consumption in terms of the weight of the train. Figure 13.5 shows energy consumption in kJ/ton km as a function of the number of seats.

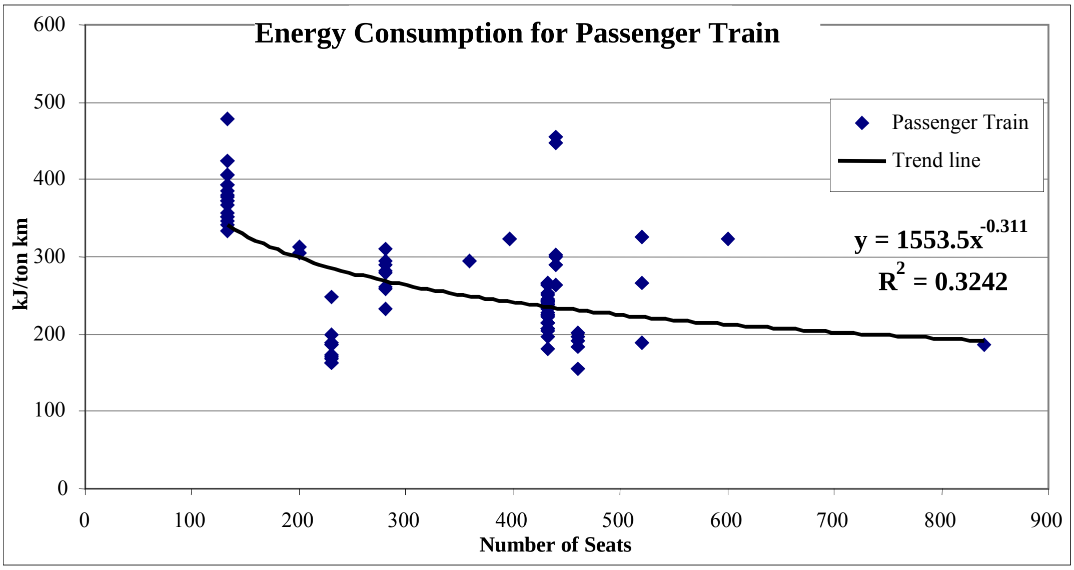


Figure 13.5. Energy consumption pr ton km as a function number of seats.

The figure shows four collections of points. These values are for the different train sets, ER, MF and MR, for each of which there is a constant number of seats. The trend

line is most affected by the train sets, especially the MR and MF, of which there are most in the data set.
The MR train has 132 seats per set, and is also that type of train that has the greatest energy consumption. This is due to the low drive train efficiency and the type of operation, which consists of unsteady operation with many starts and stops. It is also seen that the ER trains, which have 230 seats per set, diverge from the trend line if there is operation with only one set. For two or more sets, the results fall within 25% of the trend line.

The passenger train data in this way (Figure 13.5) are those that can best be described by a trend line. That is, there is a reasonable correlation between consumption per ton-km and the number of seats.
Energy consumption per ton-km and per seat-km are also shown as a function of train weight as well as the consumption per seat km as a function of number of seats. These curves are shown in Appendix 15, since these data did not lend themselves well to presentation with a trend line.

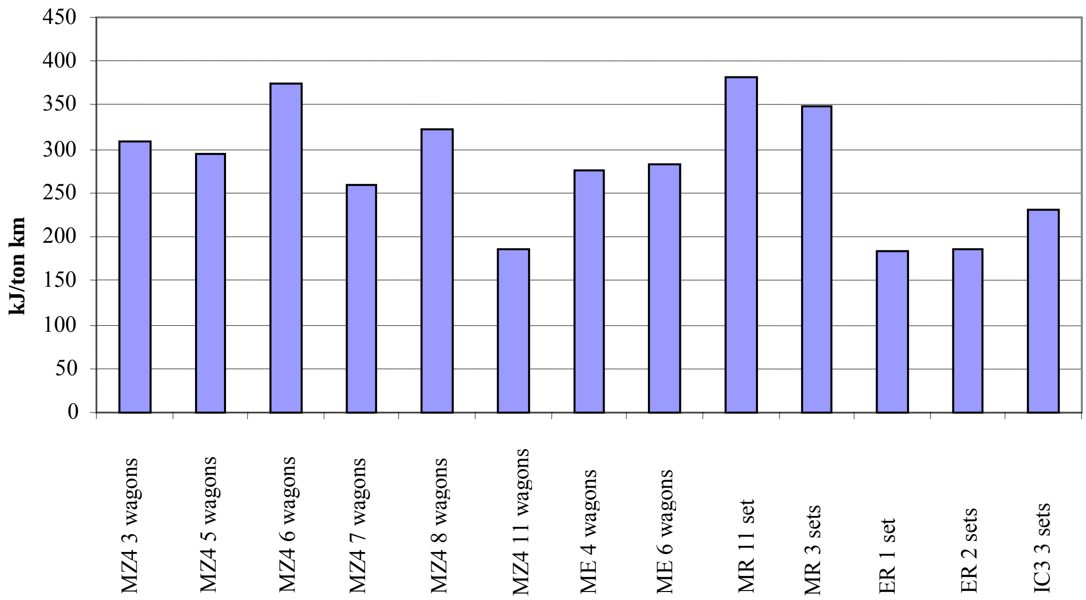


Figure 13.6 Energy consumption in kJ/ton km for passenger trains.

Figures 13.6 and 13.7 show consumption for different types and sized of passenger trains, in kJ/ton km and kJ/seat km respectively.
One would expect the consumption per ton km to decrease slightly as train size increases. This is not quite the case. It is especially the MZ4 powered train with six and eight wagons, respectively that differ. The reason for this is that average values are shown for different train arrangements. The values include operation with very

different operation patterns. Included are trains with frequent stops, trains with relatively few stops, and finally express trains that operate without stop. Operation characteristics are very important.

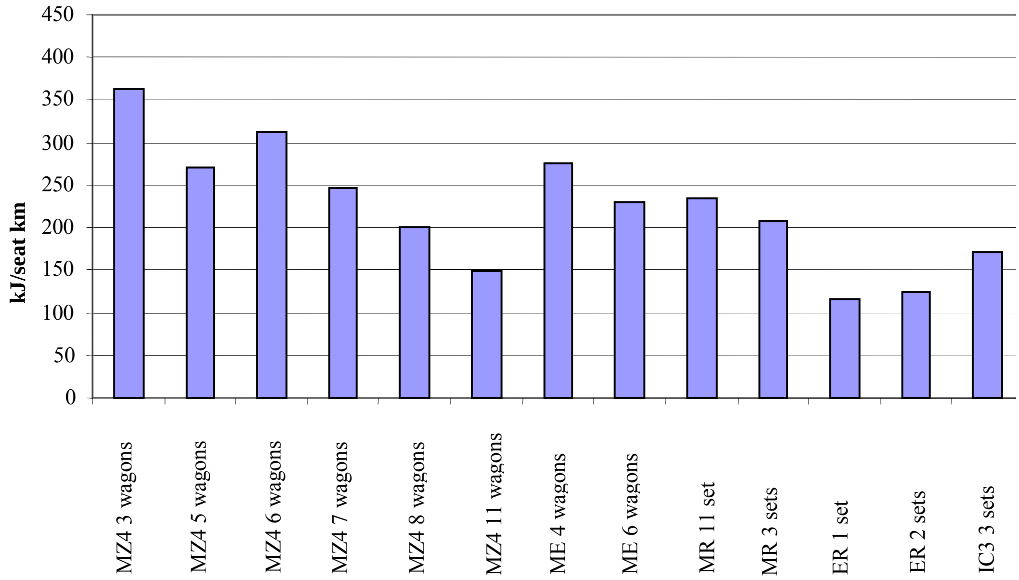


Figure 13.7 Energy consumption in kJ/seat km for passenger

For example, the MZ4 with six wagons operates on a route with frequent stops, and short distance between them, which gives a large energy consumption.
The general tendency is for the specific energy consumption to decrease and the train size increases. The MZ4 shows some exceptions to this trend.

Figure 13.7 shows the same data where the energy consumption is in terms of kJ/seat km. A similar trend to Figure 13.6 is seen. The MZ4 with 11 wagons was an express train without stops, which gives a lower energy consumption than the general tendency. Also of interest is the effect of the light weight construction of the IC3 train. Its energy consumption per seat km is relatively lower than that on the basis of kJ/ton km, indicating a higher number of seats per km.

14 Quantitative Description of Operation

14.1 Driving characteristics

In an extension of the analysis of the simulated energy consumption, the following will focus on the operation itself, and the parameters which describe the operation. Since calculations have been performed for a large number of operations, a detailed description will quickly become too large. Therefore, some average values will be presented that will give an overall comparison of the different operating patterns. Distributions of the types of operation during the operating patterns will also be presented.

The parameters analyzed are:

- Speed - Maximum and average
- Acceleration - Maximum and average
- Driving time
- Driven distance

Average values for the different types of train are given in Table 14.1.

	ER	MF	RØ	RV	Goods train
Operating time - s	9999	11195	4981	1161	4555
Distance -km	189.70	328.62	95.53	17.38	100.63
Max. speed -km/h	168.73	170.27	135.09	120.00	126.42
Ave. Speed - km/h	82.52	118.80	66.73	48.42	72.58
Max acceleration - m/s2	1.9697	0.8395	1.7803	1.9444	1.3981
Ave acceleration - m/s2	0.0255	-0.0020	0.0012	0.0354	0.0057

Table 14.1 Average values of operational data for different types of trains

Table 14.2 shows the relative standard deviation in percent for each of the parameters given in Table 14.1. The variations in speed and maximum acceleration are relatively small, since they are related to equipment and track limitations. Relative deviations in average acceleration are high due to the small value of the average acceleration.

	ER	MF	RØ	RV	Goods train
Operating time	39	8	37	210	38
Distance	31	0	42	262	51
Max. speed	6	6	8	13	14
Ave. Speed	5	4	10	16	23
Max acceleration	13	29	21	77	36
Ave acceleration	70	-46	1192	42	238

Table 14.2 Standard deviation of operational data for different types of trains

Variations in operating time and distance are related: longer routes give longer time. The values in table 14b also depend on how many routes are included for each train type. There is relatively little variation in the values for the MF train, since the operations here are only between the town of Copenhagen and Århus.

A general picture of the overall operation is shown in Tables 14.3 and 14.4. The arbitrary definition of constant speed is that two consecutive readings on the crash log were the same. The actual driving pattern distributions are of course more detailed, as shown in the figures in Chapter 12.

Operating mode	**Temporal distribution**						**Spatial distribution**				
	ER	MF	RØ	RV	Goods train		ER	MF	RØ	RV	Goods train
Acceleration	29	46	36	40	37		31	53	40	45	42
Constant speed	29	2	9	11	15		39	3	12	15	17
Stop	11	11	16	14	11		0	0	0	0	0
Deceleration	31	41	40	35	37		30	44	47	40	41
Total	1	1	1	1	1		1	1	1	1	1

Table 14.3 Distribution of operating modes in %.

Standard deviation %	**Temporal distribution**						**Spatial distribution**				
	ER	MF	RØ	RV	Goods train		ER	MF	RØ	RV	Goods train
Acceleration	41	6	36	48	45		49	5	43	48	56
Constant Speed	60	29	45	57	43		58	29	52	58	57
Stop	78	48	51	72	162		38	56	43	62	118
Deceleration	42	8	42	49	42		48	5	46	48	54

Table 14.4 Standard deviation of the values of Table 14.1 in percent

14.2 Load factors of goods trains.

The individual goods trains are often of non-uniform composition and shape. This can make it complicated to perform calculations in the case where the arrangement is unknown. This is especially true with regards to aerodynamic resistance using methods of Chapter 5. The number of axles is involved, for example, since many goods trains still have a mixture of four and two axle wagons. In passenger trains, the 4-axle wagon is most common, though with modern train sets, the situation is not as clear.

An additional problem is the usage of the train's capacity, that is the load factor. This depends on several factors. Usage can be defined in different ways, for example with respect to either volume or weight. The load capacity of the rails plays an important role, and most main rail lines in Europe today are rated to a capacity of 22,5 tons per axle. On smaller lines the load may be 20 tons, and on many private line and sidings the load limit can be on the order of 16-18 tons. None of the three parameters - spatial limitation, total weight and axle load - may be exceeded.

In the following some typical examples with be given for usage, weight and size of different train strings. The results are intended to be a supplement to the calculation of the rolling resistance, discussed earlier in this report, and in the accompanying report on technical factors for driving resistance (Lindgreen and Sorenson, 2005)

For this, a goods train is used that has been unused previously in this report, and some supplementary cases. Data on a number of goods trains was furnished from DSB. An overview of all of these can be found in Appendix 18.
There will also be calculated values for the limits on the basis of data for the different wagons. Among the parameters calculated are:

- Weight per wagon axle.
- Goods weight per wagon.
- Goods weight on the train.
- Loading per train (wagon + goods).
- Degree of utilization.
- Number of axles per wagon.
- Tare weight per train.

The actual data is calculated from the following parameters: Goods weight, loading weight and total number of wagons.

The weight per wagon may be calculated

$$m_w = \frac{\text{loading weight} - \text{goods weight}}{\text{number of wagons}} \tag{14.1}$$

From this, the number of axles per train can be calculated. The weight per wagon gives an indication of whether the train consists mainly of two or four-axle wagons. Since the axle loading may not exceed 20 tons, that is 40 tons for a two-axle wagon and 80 tons for a four-axle wagon, an estimate of the average number of axles per wagon can be made. The loading factor, Lm, can be calculated as:

$$L_m = \frac{\text{Goods weight}}{(40 - \text{weight per wagon}) * \text{total number of wagons}} \tag{14.2}$$

The weight per axle, m_{pa}, can then be calculated as:

$$m_{pa} = \frac{m_w}{n_{ax,w}} \qquad (14.3)$$

and the weight of goods per wagons as:

$$m_{goods,w} = \frac{\text{goods weight}}{\text{number of wagons}} \qquad (14.4)$$

The maximum load capacity for a complete goods train is calculated as:

$$\text{Max cap} = \frac{20 - \text{tare weight per axle}}{\text{number of wagons} \cdot \text{number of axles per wagon}} \qquad (14.5)$$

Data for the wagon types chosen is shown in Appendix 17.

The trains were analyzed, and the results are shown in Table 14.5 as average values for all goods trains or wagon types.

	All goods trains in use:	Unweighted fleet average at capacity (see appx17?)
Goods weight per wagon:	13.64	47.86
Tare weight per wagon:	20.89	21.60
Tare weight per axle:	7.09	7.13
Total weight per wagon:	34.53	67.00
Goods as % of total weight :	39	67
Goods as % of capacity:	29	100
No. axles per wagon:	3.06	3.09
Weight/axle:	7.09	14.68
Goods weight per train:	156.67	465.96
Weight per train: (less loco)	404.88	-
Wagons per train:	13.6	-
Max weight per axle:	-	21.81
Weight per m:	-	3.83
Length per wagon:	-	17.24

Table 14.5. Characteristics of a group of Danish railway goods trains, all weights in tons, traffic in 1999.

It can be seen that for the Danish fleet reported:

- The utilization of the wagons’ load carrying capacity by weight is about 30%.

- The average weight of the goods is about 39 % of the total weight of the cars (no loco).
- The average number of axles per wagon is about 3. This is about the same as the average for all the types of wagons, not weighted with respect to number of wagons.
- An average Danish goods train is 343 m long (17,25m/wagon·13,6wagons per train)
- An average train weighs about 405 tons, without a locomotive, about 525 with the locomotive.

The data above used because they were available, and it is not known how representative they may be for the entire Danish fleet or for fleets in other countries. The results include trips between major cities, and som routes to smaller town. There few trains over 600 tons, though there is a train in the data set with 40 wagons, with a goods capacity of about 1750 tons. While the average utilization was about 30 % of cargo carrying capacity, the range was between 7 and 96 percent, reflecting almost completely full trains and almost completely empty trains.

Some additional information was available from DSB and is shown in Appendix 19. The data are from two years earlier, around the time of the opening of the bridge and tunnel across the Great Belt. The entire network is included in the calculation. It shows an average of about 250-260 tons of goods per train, compared to 157 in Table 14.5, indicating that the data in Table 14.5 probably has an over representation of smaller trains. It can be seen that there are many trains with fewer than 10 wagons. The average number of wagons per train can be calculated from the data in Appendix 19, and the results are 16, 16,7 and 14,4 for the diesel powered trains and 22, 22 and 20 for the electric trains. The latter would only be operating on the main line between Copenhagen and the provinces over the Great Belt, and would be expected to be larger. Diesel powered trains could also use the Great Belt connection, but diesel power is exclusively used on the branch routes to small cities, hence the smaller trains. Note that the trains in Table 14.5 are all diesel powered, and in this regard, include more small trains the electric trains on the mainlines. The train loading for diesel trains are comparable, 13,6 tons goods per wagon in Table 14.5 compared to between 13,6 and 16,2 from Appendix 19.

Accordingly, the number of wagons per train in Table 14.5 most closely agrees with the diesel trains of Appendix 19. The loading factors would also be fairly close to those of Table 14.5. It is more difficult to give a load factor for the electric powered trains. Appendix 19 shows that the electric trains have greater weight of goods per wagon than the diesel trains. But if the diesel trains have a higher percentage of small, two-axle wagons, this does not necessarily mean a higher load factor, as there could be a higher percentage of four axle wagons, in keeping with the route. Lacking more information, it is probably most reasonable to assume that the relative capacity utilizations of Table 14.5 probably are acceptable estimates for all trains.

15 Improved Aerodynamics

The construction and arrangement of wagons in a train are some of the most important parameters in connection with the determination of the driving resistance and consequently the energy consumption for a train operation. A poor aerodynamic shape will give a larger airflow coefficient C_L, and with that a larger air resistance and accompanying increased energy consumption. A potential improvement of aerodynamics is most apparent for a goods train, since they often consist of wagons with a wide range of sizes, shapes and arrangement.
Improvements for passenger trains must be performed in connection with the construction of the train/wagons, since passenger trains normally are quite homogeneous, since they consist of a number of the same wagons.

Goods trains have a difference structure and shape, and vary much more than passenger trains. With the exception of mail trains and unit trains, the arrangement of goods trains is often a mixture of different types of gods wagons with different sizes and shapes.
The following will investigate the effect of composition and structure of different goods trains on their energy consumption. Variations in goods wagon type and the influence on rolling resistance parameters has been presented in the accompanying report (Lindgreen and Sorenson, 2005).

For the goods trains investigated here, the actual arrangement of cars was not known. But since the C_L-values are approximately known, it is still possible to say something definite about their construction and shape. The operations with the trains under consideration with then be compared with conditions where the same train is changed to given a homogeneous shape, that is all wagons of the same shape. In practice then this will correspond to calculation of the train as if it was homogeneous and then compare the results with the correct results for the real arrangement of the train.
The object is to illustrate the effect of homogeneity on the energy consumption and emissions. This can give an indication of the amount of energy and pollution than might be saved if the cars were covered, or at least of all the same shape.

It was decided to simulate a selection of the goods trains that were utilized in Chapter 13. The post train is not included, since this is already homogeneous. In order to obtain observable trends, the trains were first and foremost chosen on the basis of:

- Train weight,
- Length of the train

- Value of C_L
- Number of wagons

Using these criteria, the following trains were chosen:

Train no.	**From**	**To**	**wagons**	**Weight (t)**	**Goods weight (t)**	**Length (m)**	**C_L**	**$C_{L,hom,sgis}$**	**$C_{L,hom,Gls}$**
G9425	Gb	Kj	36	1439,36	878	490	7,4	6,3	4,7
G9217	Gb	Rg	39	1202,24	357,6	560	10	7,1	5,2
G9409	Gb	Kj	25	2158	1358	520	7,5	6,6	4,9
GS7495	Rg	Fa	29	791,38	232	430	6	5,6	4,2

Table 15.1 Trains Chosen for the simulation of the effects of aerodynamics.

No simulations were performed on any other variations of inhomogeneous trains, since the objective was to evaluate the potential saving in energy consumption of the optimal solution. As the reference for the homogeneous goods train, that is the type of wagon which is used to calculate $C_{L,homogen}$ both a two axle and four axle good wagon were chose. Descriptions of and data for the wagons used are found in (Lindgreen and Sorenson, 2005). The four axle wagon is a container wagon of type Sgis with full load, and therefore homogeneous, and well as a two axle wagon Gls, which is a closed goods wagon. $C_{L,homogen}$, is the air resistance coefficient for the homogeneous train and is calculated from the length of the train:

Sgis: $C_{L,\hom ogen} = 0{,}867 + L_T \cdot 1.11 \cdot 10^{-2}$

Gls: $C_{L,\hom ogen} = 0{,}94 + L_T \cdot 7{,}61 \cdot 10^{-2}$

Table 15.2 shows the energy consumption for each of the four goods trains considered. The energy consumption is based on the spatial distribution of operating conditions E(X%), which has been shown to be very close the that of the temporal distribution. Only changes in energy consumption are given, since the model uses average fuel specific emissions factors.

Train	**Actual arrangement**	**Homogeneous four axle**		**Homogeneous, two axle**	
	kJ/ton-km	kJ/ton-km	%	kJ/ton-km	%
G9425	179	175	0.98	170	0.95
G9217	175	164	0.94	157	0.90
GS9409	168	166	0.99	162	0.97
Gs7495	204	201	0.98	189	0.92

Table 15.2 Simulated energy consumption of goods trains with conventional heterogeneous composition, and with homogeneous wagon type.

The energy consumption in Table 15.2 is given in terms of kJ/ton-km, based on the total weight of the train.

The results indicate that there are only relatively small saving in energy consumption. The amount of the savings depends on how much the air resistance coefficient C_L can be reduced. It must also be recalled, that the air resistance is only a part of the total resistance to motion, and the lower the speed of the train, the less the benefit. Table 14a shows that the maximum speed for the goods trains is 126 km/h and that the average speed is 72 km/h. The relatively low speeds will reduce the savings due to aerodynamic improvement for goods trains. A speed over 130km/h is expected to be rare for a goods train.
The largest savings was estimated for the train G9217. C_L, was reduced from 10 to 7.1and 5.2, for the four and two axle cars. This gave a reduction in fuel consumption of 6% with the four axle wagons, 10% with the two axle wagons. Similar changes in the train GS9409 gave the lowest savings of 1 and 3% respectively for the four and two axle wagons.

The savings are not that large. Considering what it would require to make the changes discussed, a larger saving would probably be necessary. Considering that many modern goods wagons have four axles, which means the potential savings are smaller, it would probably not be sufficient to change aerodynamics alone. Especially not, because it would increase transit time to perform the covering, and thereby make the transport less effective.

16 Auxiliary Energy Consumption for Passenger Trains

16.1 General.

Most of the energy used by a train is used for maintaining motion. In addition, there are other needs for energy, among them:

- Cooling
- Electrical Equipment and transformers in the locomotive
- Pumps and Compressors
- Losses in engine and transmission
- Charging of batteries
- Power for passenger cars

16.2 Power Consumption in Locomotives

The following is a supplement to the material of Chapter 5, where the different forms of transmissions were considered. For electric locomotives, there are both losses in the transformation of the electricity and in the transmission system.

Main Elements of an electric locomotive

- Transformer. Receives electricity from the wires and converts it to a form compatible with the internal requirements of the train.
- Current rectifier. Converts AC to DC.
- Traction motor. The electric motor that directly drives the locomotive wheels.
- Intermediate circuit. The unit between the rectifiers..
- Gearing. The gear train between the traction motors and the wheel axles
- Net: Cables and wires

For diesel locomotives there is a series of individual loss sources from the diesel engine and transmission system. These are named in Chapter 5. .

In addition, there is auxiliary equipment, which is found for both electric and diesel locomotives:

- Ventilation:
- Oil pumps:
- Compressor:
- Electronics:

In addition to the power needed for cooling, it is also necessary to keep batteries charged for starting a locomotive, among other things. This power is of small importance though, in the overall picture. Figure 16.1 shows the different sources of losses in a modern electric locomotive. (Re 460):

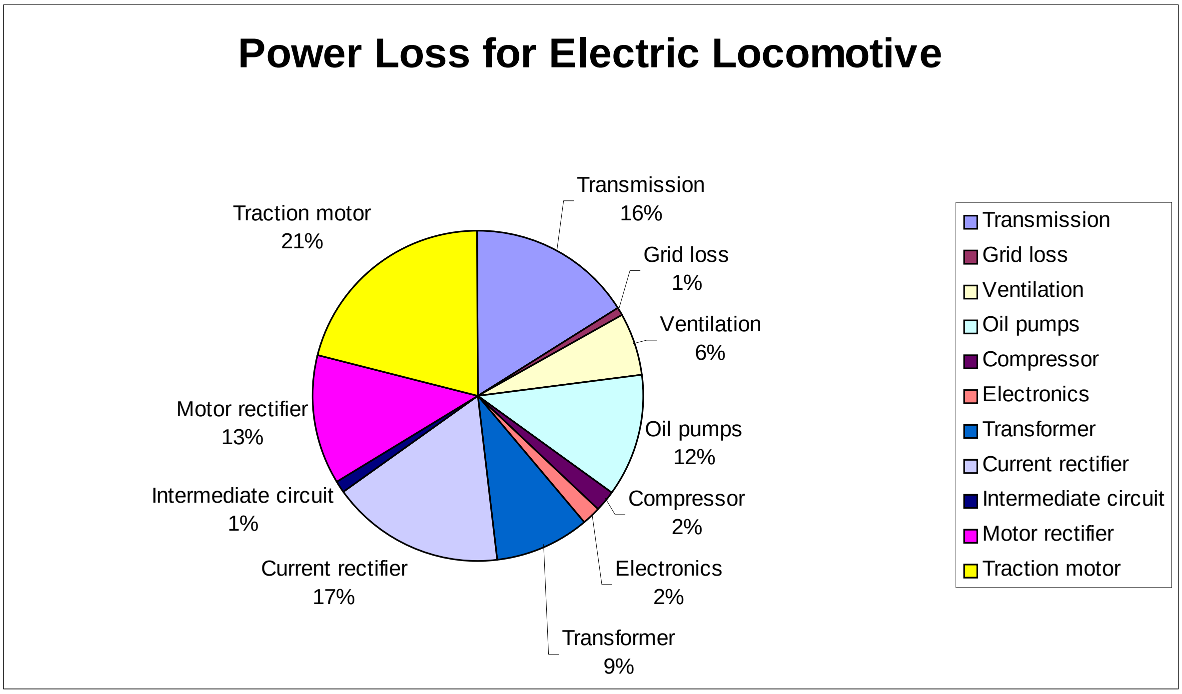


Figure 16.1 Power Losses in an Electric Locomotive.

This figure shows that the largest loss is that in the traction motors, which comprise about 20% the total loss. The mechanical loss in the gear train between the traction motors and the wheel is next in importance, as well as the rectification of the electricity from the net cables. (Mayer , 2000)

16.2 Auxiliary power and equipment in the wagons

The energy requirements named above are common for most trains. There are some differences, depending on whether it is diesel or electric power. For example, an electric motor has much different losses than a diesel engine.

For a passenger train, another type of power need comes into play. In contrast to a goods train, the passenger train needs power to provide for human comfort. The most important needs are:

- Heating and Air conditioning.
- Lighting

- Other purposes: Toilet systems, possible catering equipment, door opening systems, brakes, and public address/music systems.

The power requirements for heating and air conditioning depend on the temperature of the wagons, the efficiency of the equipment as well as air exchange in the wagon, (open windows etc.) and the power of the air conditioning equipment. The lighting consumption depends on the type of wagon and the number of lighting fixtures. Normally, neon lamps are used. They have low power consumption under operation, but high consumption when started, the latter being infrequent. The lighting load is fairly uniform for passenger trains. Of the remaining losses, the net losses and compressed air supply are among the most important.

Figure 16.2 (Brunner, et. al. 1998) shows a distribution of typical relative auxiliary power consumption for a passenger wagon. The numbers describe the power consumption for a normal passenger wagon. Here, it is a wagon of 44 tons. The wagon's yearly energy consumption is a total of 690 MWh/year

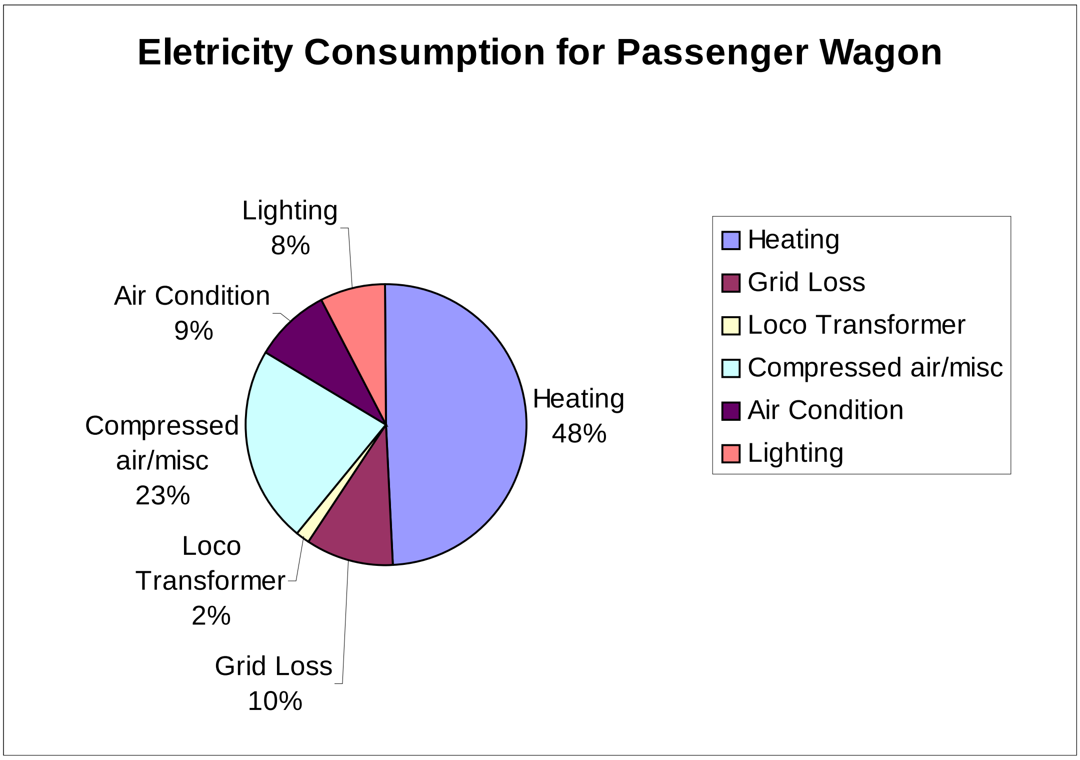


Figure 16.2 Energy consumption distribution for a passenger wagon.

The figure shows that about half of the power goes to heating. Since this is about half the total energy use, a closer investigation is of interest. The purpose of the heating is, of course, to maintain the temperature in the wagon at a level conformable to the passengers. The annual usage depends on factors such as:

- The desired temperature of the wagon, both when in operation and when parked. The internal temperature is almost constant year round when in operation. It can be lower when the wagon is parked, but in cold climates, freezing temperature may cause damage. The external temperature can vary from well below freezing to over 40°C.
- The insulation of the wagon, type of material, amount condition as well as rust and leaks are important factors in the energy consumption for heating/cooling
- The number of stops is important, in that opening the doors causes exchange of outside and inside air.
- The number of doors as well as the number of windows that can be opened play a role in the heating/cooling requirements.

As an extension of the above, Figure 16.3 shows the annual variation in the electrical consumption of a passenger train (Brunner, et. al. 1998).

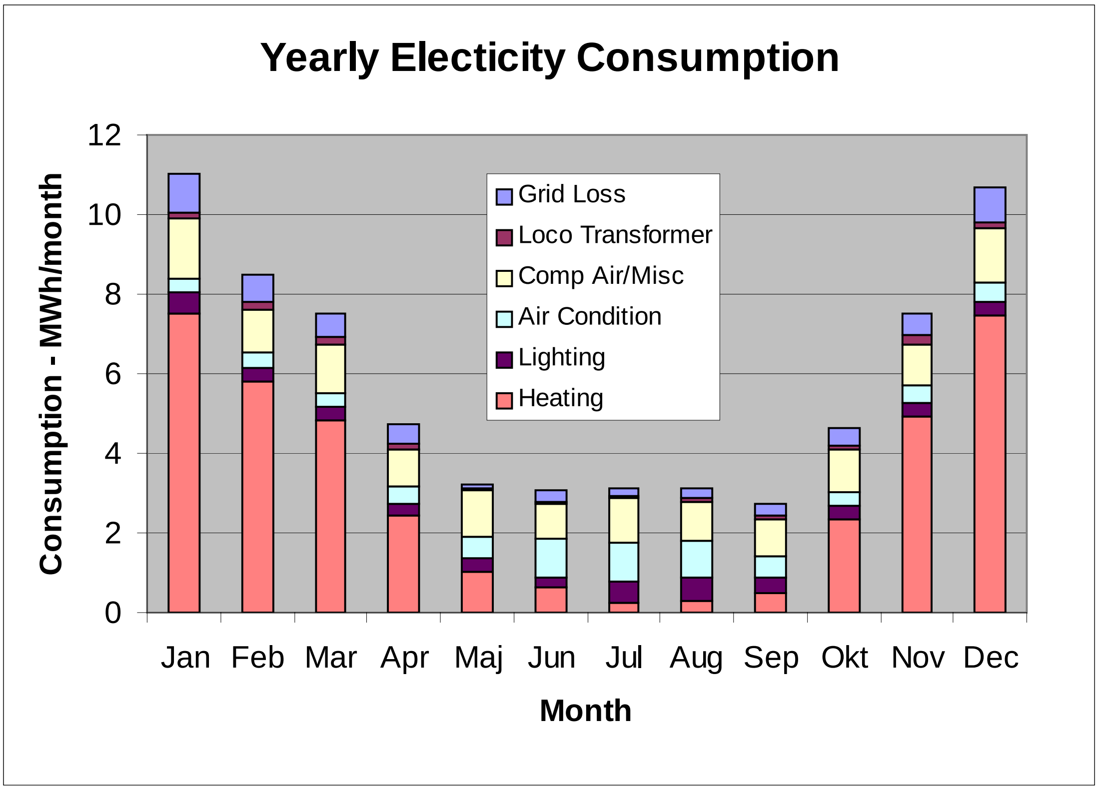


Figure 16.3 Annual distribution of electricity consumption of a passenger

The figure shows that not only is heating the most important factor, but it is also the factor that varies the most throughout the year. The consumption for heating varies by a factor of about 20 between summer and winter. The air conditioning also varies throughout the year, but only by a factor of about two. The grid loss in the locomotive transformer (which converts to power for the wagons) varies also, but this is due to the variability in the heating and air conditioning requirements. The power for the brakes and lighting are roughly constant.

16.3 Power loss for passenger trains as a unit.

After looking at the passenger wagon and locomotive's individual losses, attention is now focused on consumption and loss for an entire passenger train. The train examined consists of an electric locomotive and eight two-story passenger wagons. The total power requirement and the corresponding losses are shown in Figure 16.4 (Meyer, 2000)

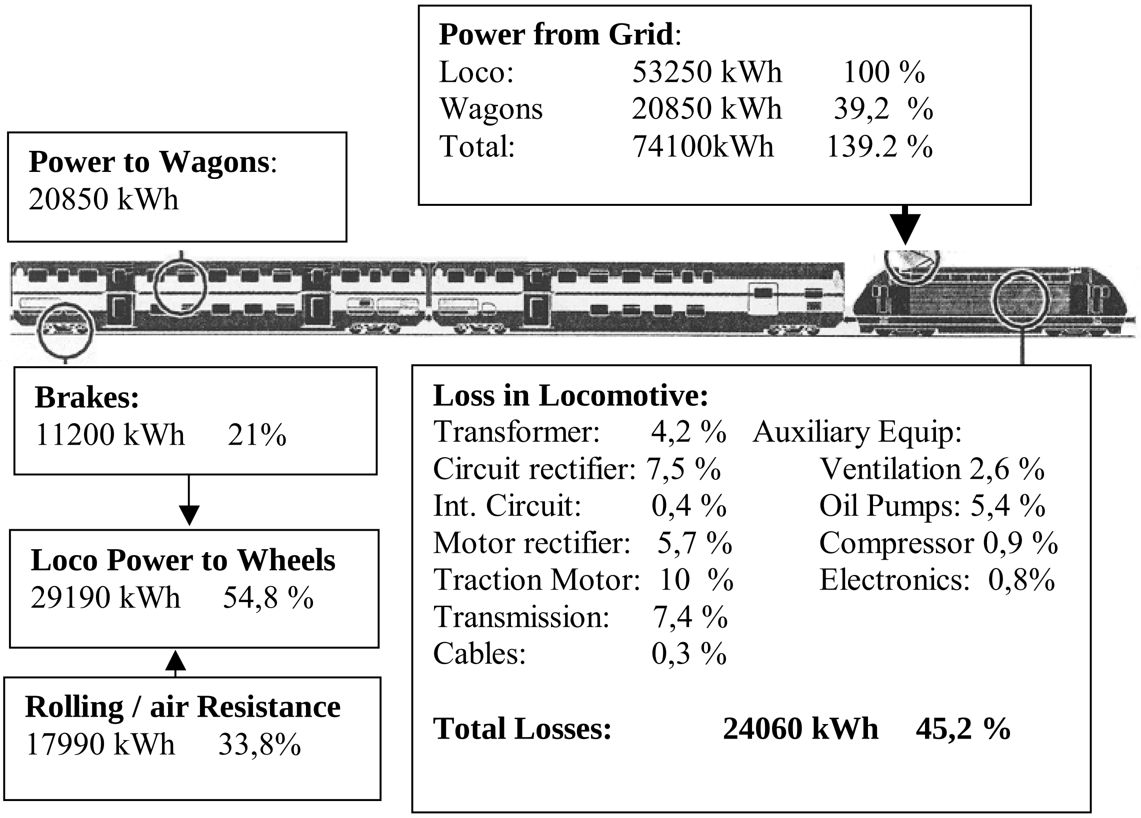


Figure 16.4 Loss and power consumption for a Swiss electric locomotive and eight wagons.

It is assumed that the locomotive losses are typical of a modern electric locomotive. These values for losses were also used for the type ER train. The total energy collected from the power lines is 74100 kWh. The locomotive uses almost 72% of this. That is, the wagons alone use almost 30% of the total energy consumption of the train. The figure shows that only 54,8% of the locomotive's consumption of 53250 kWh goes to direct propulsion of the train. Of this, 62% (33,8% total) goes to overcome rolling and air resistance. The traction motors, rectifiers and the transmission make up the largest sources of losses.

17 Conclusion

The purpose of the work has be to construct a model for the calculation of the energy consumption and emissions on the basis of driving patterns divided in an operating matrix. The advantage of the matrix approach instead of actual driving patterns is that it is faster to use, more transparent, but most of all because it permits greater versatility and flexibility. An analysis of any driving pattern can be performed, or a collection of driving patterns, which can be described in a statistical fashion in terms of frequency of operation conditions. An Excel program using macros has been constructed to perform this.

The model has been tested by simulation a series of different regional and international passenger trains and goods trains using a variety of driving patterns. The results have been compared to detailed simulations and experimental results from DSB, using engine data and engine operation collectives.

The following accuracy was obtained

- For locomotive powered passenger trains the average deviation was about. 8%
- For passenger trains operated with the MR-train set the average deviation was about 7%.
- For Goods train the average deviation from the DSB values was about 15%. There were a few deviations up to about 25%, but it was assumed that this is due to uncertainty in the data for the quantity of goods relative to the different stops.

It is concluded that the model has an acceptable accuracy for energy consumption. The accuracy appears best for passenger trains. By comparison with detailed simulations of full driving patterns, the utility of the matrix approach to driving characteristics can be said to be confirmed.

Though it must be pointed out that the model still uses emissions factors that are not condition dependent, that is to say the emissions for all modes are the same, average value. This gives larger deviations for HC, CO and particle emissions, which in general are more on operational and design differences than CO_2 and NO_x, for which the agreement with DSB data is best.

Acceptable results can be obtained with an operational matrix with a relatively small number of elements. Sensitivity to the number of elements is greater for the acceleration than the velocity.

Sensitivity to rolling and air resistance for the trains examined has not been great. In this regard, it should be recalled that the trains compared to data do not included very long distance trains like high-speed trains. Here the rolling and aerodynamic resistances should be more important, since there are fewer accelerations. In the trains covered here, stops and starts are more frequent, giving a greater dependence on train weight. Effects of gradient resistance have been limited, but the terrain covered in the model development to data has been fairly flat.

The model has been used to analyze operations for different types of trains, and trains with different driving patterns. Simulations have been conducted to investigate the effect of the following three factors on energy consumption:

- Number of stops
- Nature “quality” of the operation
- Maximum speed

Different operation patterns for regional passenger trains were analyzed on the approx 65 km Danish Coast line to illustrate the effect of the number of stops on energy consumption. Simulations were performed for express trains, rush hour trains without some suburban stops, and trains with stops at all stations

- Operation without stop results in a reduction of energy consumption of about 50-56% relative to stopping at all stations.
- By stopping at a selected number of stations, energy consumption was reduced by about 20-36% relative to stopping at all stations.

The effect of the nature of the operation was simulated using two goods trains with MF power between Copenhagen main station and Høje Tåstrup. For this trip of about 20 km, extra stopping and slow-down from signals and capacity limitation gave in increase in energy consumption of about 50 %.

The intercity IC-train was used to examine the effect of maximum speed on a stretch of about 120 km between Copenhagen and Korsør. Smooth, normal operation was used for all patterns, and simulations were performed with maximum speeds of 140, 160 and 180 km/h.

- By reducing the maximum speed from 180 km/h to 140 km/h, a reduction of energy consumption and emissions of between 20 and 25% was obtained.

- By reducing the maximum speed to 160 km/h a reduction of between 10 and 14% was achieved.

A reduction in maximum speed results in a decrease in energy consumption at the expense of an increase in travel time.

In addition, a series of simulations were performed with actual Goods trains to investigate how much energy reduction was possible by reducing the aerodynamic resistance for non-homogeneous trains, that is, trains with a variety of different goods wagons. The effect of covering the wagons was to make the trains uniform and therefore reduce aerodynamic resistance.

The largest reductions found were 10 and 6% with the use of two and four axle wagons respectively. Averaged over a larger number of operations, the reductions were between 2 and 6%, which is felt to be a small reduction given the effort required to do this in practice.

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List of Appendices

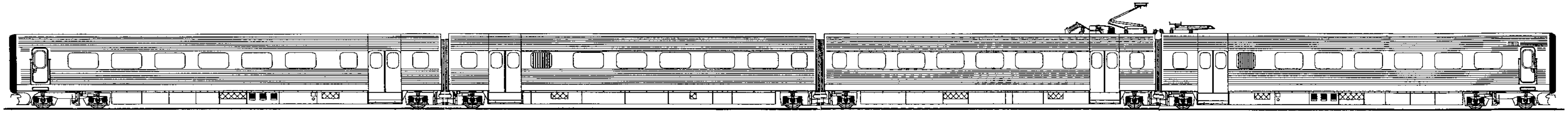
Appendix 1 Selected Equipment

Equipment

Source: DSB Materiel i Drift. DSB materiel 1996.

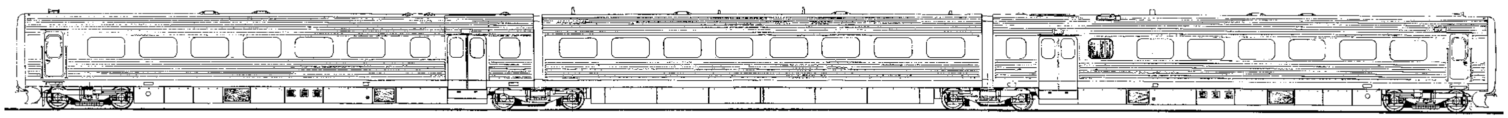
ER

Motor:	4 - 420 kW
Transmission:	Electric
Max. Speed:	180 km/h
Length:	76,53 m
Width:	3,10 m
Height:	3,85 m
Service weight	133,0 tons
Seats:	230
Max. size:	5 train sets



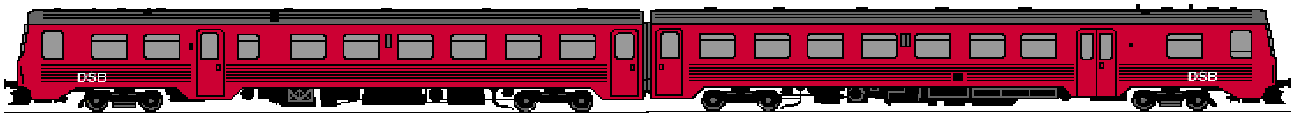
MF (IC3)

Motor:	4 - 294 kW
Transmission:	Diesel mechanical
Max. Speed:	180 km/h
Length:	58,80 m
Width:	3,10 m
Height:	3,85 m
Service weight	97,0 tons
Seats:	144
Max size:	5 train sets



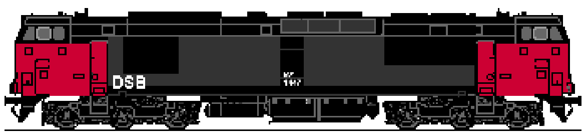
MR-MRD

Motor:	Two - 237 kW
Transmission:	Diesel hydraulic
Max. Speed:	130 km/h
Length:	44,68 m
Width:	2,88 m
Height:	3,81
Service weight	69,0 tons
Seats:	132
Max. Size:	5 train sets
Controller steps	7



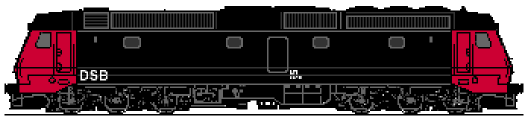
MZ4

Motor:	GM 20-645 E3
Max. Power	2685 kW
Transmission:	Diesel electric DC
Max. Speed:	165 km/h
Length:	21 m
Width:	3,03 m
Height:	4,28
Service weight:	123 tons
Start tractive force:	410 kN
Controller steps:	8



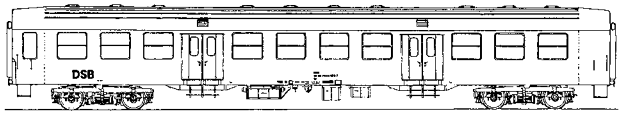
ME

Motor:	GM 16-645 E3B
Max. Power	2460 kW
Transmission:	Diesel electric AC
Max. Speed:	175 km/h
Length:	21 m
Width:	3,15 m
Height:	4,35
Service weight:	115 tons
Start tractive force:	360 kN
Controller steps:	8



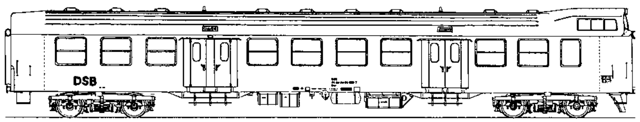
Bn

Max. Speed	160 km/h
Length	24,50 m
Width:	3,04 m
Height:	4,05 m
Axle distance	: 17,20 + 2,50 m
Floor height:	1,21 m
Service weight:	36,0 t
Seats	80



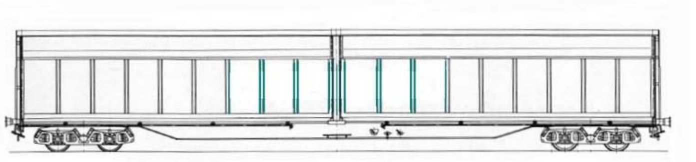
ABns

Max. Speed	160 km/h
Length	24,50 m
Width:	3,04 m
Height:	4,22 m
Axle distance:	17,20 + 2,50 m
Floor Height:	1,21 m
Service weight:	37,5 t
Seats	40



Habbinss-y

Manufacturer	Rautaruukki
Date	1997
Max. Speed	140 km/h
Max. Load	63,0 t
Tare weight	27,0 t
Length	23,24 m
Axle distance	17,70 + 1,80 m
Floor Height	1,20 m



Appendix 2 Load collectives

21. for RØ4557. Østerport-Kalundborg

Main data

Litra-Number	No. wagons	Seats	Distance km	V-max (km/h)	Train length (m)	Date/Time
MZ 1458	8	600	113.81	140	220	25.03.99

Calculation results:

Controller-step	Time (sec)	Time (%)	Dist (km)	Dist (%)
0	3131	51	38.425	34
0	101	2	3.27	3
2	157	3	4.335	4
0	138	2	3.635	3
4	518	8	13.28	12
1	166	3	4.915	4
6	135	2	3.655	3
1	125	2	2.11	2
8	1716	28	40.185	35
Sum	6187	101	113.81	100

Load Collective

Controllerstep	Fuel	CO2	NOx	HC	CO	Particles
	kJ	g	g	g	g	g
0	869009.050	63895.883	1376.247	154.366	424.532	34.300
1	47439.700	3386.783	68.893	4.784	10.312	1.222
2	167597.500	12097.949	176.966	8.630	22.787	5.666
3	259274.400	18798.774	319.888	9.491	19.517	10.162
4	1327116.000	98468.174	1716.691	41.484	80.995	59.253
5	588320.600	43512.335	688.739	17.460	49.502	31.240
6	613919.250	46042.020	706.093	17.064	90.950	27.092
7	789950.000	59874.438	1051.448	23.026	137.027	31.260
8	12932719.800	979386.408	17225.517	427.552	2383.751	439.747
sum	17595346.300	1325462.762	23330.482	703.857	3219.372	639.942
per km	154602.814	11646.277	204.995	6.184	28.287	5.623
per seat-km	257.671	19.410	0.342	0.010	0.047	0.009

Emissions

2.2 Load collective for GP7523. Glostrup-Fredericia

Main data

Train type:	GP
Litra:	ME1505
Train No.:	7523
From station:	Gl
Planned departure :	22:45
To station:	Tov
Planned arrival:	26:20:00
Litra-Number	1505
Date/Time	04.05.99
Afstand	320

Weight (tons)	
at coupler	314
Goods	126
Tare wieght	188
Total	429

Calculation results:

Controller-step	Time (sec)	Time (%)	Dist (km)	Dist (%)
0	4549	37	85.91	27
1	693	6	20.595	6
2	459	4	10.915	3
3	780	6	23.13	7
4	1379	11	45.525	14
5	1130	9	31.35	10
6	822	7	23.805	7
7	173	1	6.18	2
8	2547	20	72.705	23
Sum	12532	101	320.115	99

Load Collective

Controller step	Fuel kJ	CO2 g	NOx g	HC G	CO g	Particles g
0	1359696.1	100578.39	2247.6609	230.6343	395.3081	24.1097
1	207137.7	15336.09	354.0537	31.2543	41.5107	3.8115
2	352787.4	26273.16	523.5354	31.0743	42.687	7.1604
3	1032486	76182.6	1589.094	69.186	78	37.362
4	2826398.4	214062.17	4524.6369	159.2745	167.9622	144.9329
5	3232817	245243.9	5093.701	159.556	192.778	218.881
6	2983449	228244.74	4619.8044	145.7406	253.9158	167.6058
7	864290.7	66753.78	1259.3535	40.6031	206.2333	49.0974
8	15225966	1181069.37	21529.791	739.1394	4391.028	901.638
sum	28085028.3	2153744.2	41741.6308	1606.462	5769.423	1554.599
pr km	87734.184	6728.0329	130.39577	5.0184	18.0237	4.8564
pr.tonkm	204.5086	15.68306	0.3040	0.0117	0.04204	0.01134

Emissions

2.3 Load Collective v for RV4219. Aalborg-Frederikshavn

Main data:

Ttrain type:	RV
Litra:	MR4090
Train No.:	5249
From station:	Ålborg
Planned departure:	18.46
To station:	Frederikshavn
Planned arrival:	19.55
Ttrain length	50
Date/Time	23.06.99
Afstand	84.7
Number of seats	132

Calculation results:

Controller-	Time	Time	Dist	Dist
step	(sec)	(%)	(km)	(%)
0	1671	41	21.865	26
1	132	3	2.845	3
2	173	4	3.46	4
3	59	1	1.76	2
4	353	9	11.07	13
5	44	1	1.3	2
6	343	8	10.89	13
7	1338	33	31.51	37
Sum	4113	100	84.7	100

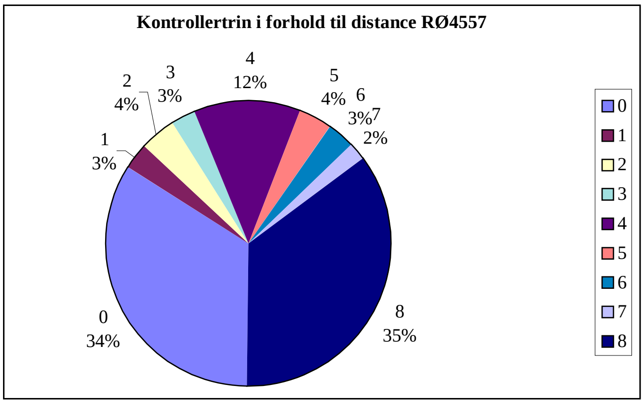
Energy consumption and emissions:

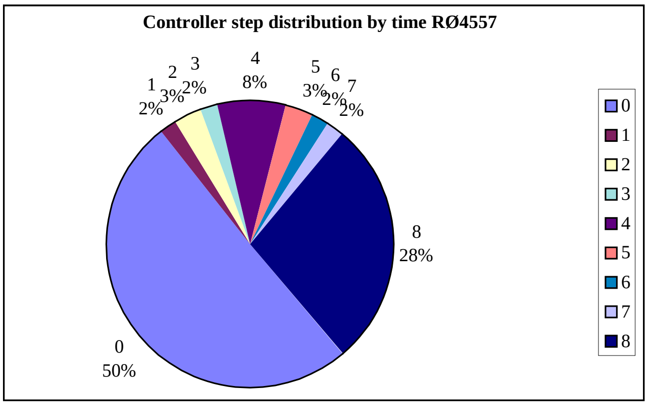
Controller	Fuel	CO2	NOx	HC	CO	Particles
step	kJ	g	g	g	g	g
0	142703.4	11505.67	114.8562	198.2291	345.8118	72.77372
1.04	33818.4	2304.06	30.67931	16.42027	23.30962	6.578022
2	66483.9	4394.823	53.13487	18.95976	40.26575	7.370319
3.04	30231.6	2169.459	28.28212	5.001489	10.86332	2.0632
4	256242.7	18047.73	272.2283	20.62226	46.53317	10.16658
5.04	38515.4	2782.824	47.82923	1.986248	4.15228	0.948024
6	366152.5	26412.27	481.7888	13.70765	26.98004	6.643395
7.04	1828243.2	130313.2	2201.723	86.03842	203.8486	59.42526
sum	2762391.1	197930	3230.522	360.9652	701.7646	165.9685
per km	32613.83	2336.836	38.1408	4.2617	8.2853	1.9595
perseat-km	247.07	17.7033	0.2889	0.0323	0.0628	0.0148

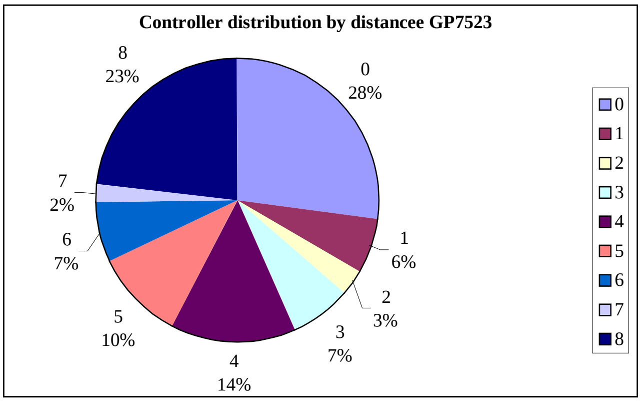
Actual emissions factors compared to the models emissions factors.

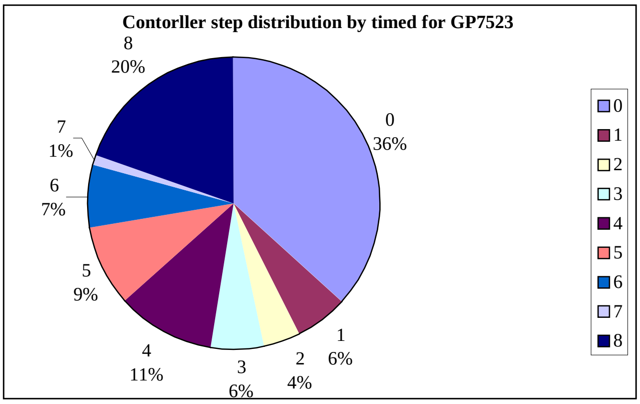
	CO_2 [g/MJ]	SO_2 [g/MJ]	NO_X [g/MJ]	HC [g/MJ]	CO [g/MJ]	Particles [g/MJ]
DSB RØ4557	74.70302	0.017088	1.258692	0.040144	0.327274	0.046985
DSB GP7523	76.60984	0.017088	1.473317	0.054166	0.211474	0.056108
DSB RV5249	71.42087	0.017088	1.165698	0.130250	0.253224	0.059888
Model	74,44	0,075	1,32	0,066	0,246	0,076

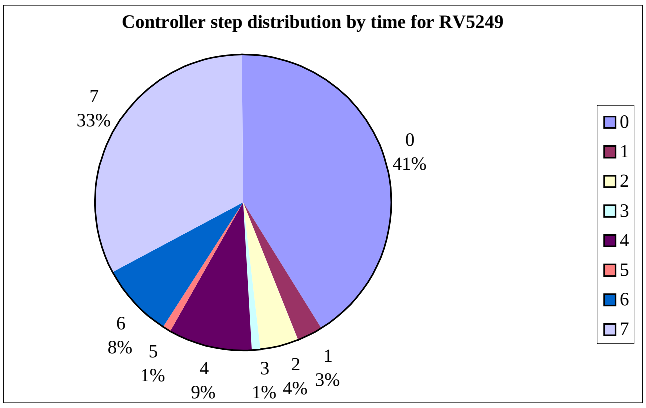
2.4 Controller step distribution with respect to time and distance for RØ4557, GP7523, and RV5249

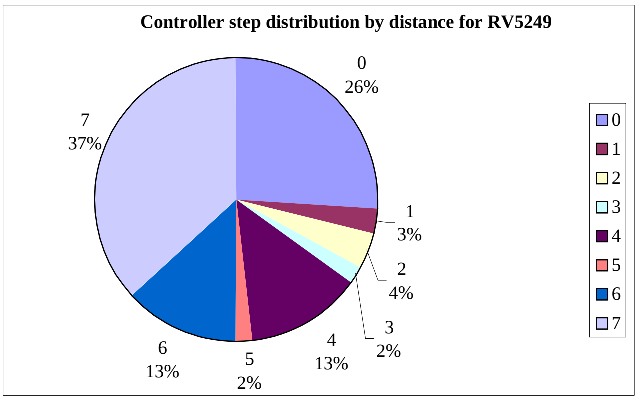












Appendix 3 Data and values for calculation of C_L and C_R

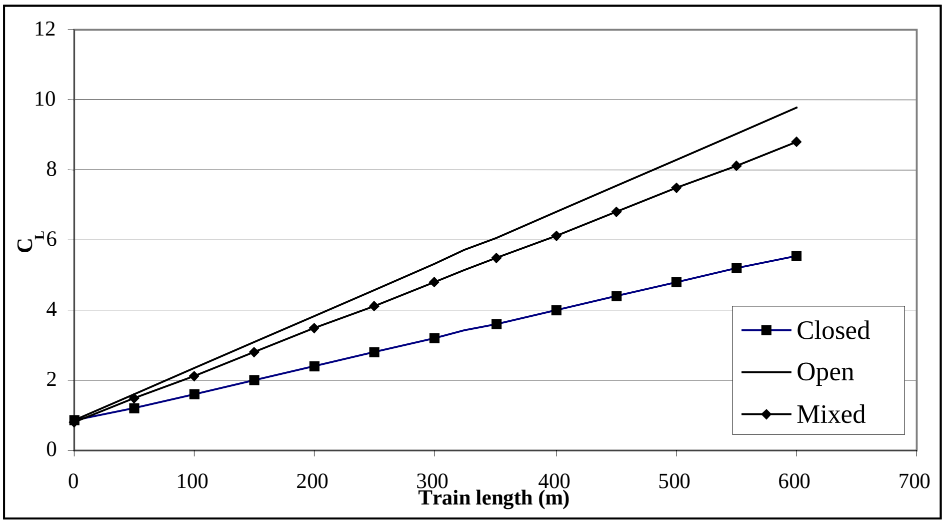
Dato	Togløb	Fra	Til	Lokomotiv	C_L	C_R	x (m)	t (s)	v_{snit}	C_0	C_1	C_2	f_{SL}	m_L	f_{SV}	m_V	m_{tog}	c_{SV}	F_{a1}	n_{ax}
24/2 99	IN392	Kh	Hg	MZ1457	1.87	2.42E-03	45745	2009	22.77	1.879E-03	0.00025	0.0005	0.004	123000	1.133E-03	349600	472600	0.0004	100	34
25/2 99	IN 392	Kh	Hg	MZ1457	2.31	2.19E-03	45765	2064	22.17	1.674E-03	0.00025	0.0005	0.004	123000	1.155E-03	551200	674200	0.0004	100	50
26/3 99	RØ3061	Hg	Kh	MZ1458	1.76	2.83E-03	185526	6900	26.89	2.122E-03	0.00025	0.0005	0.004	123000	1.211E-03	253500	376500	0.0004	100	30
25/3 99	RØ4557	Kk	Kb	MZ1458	1.98	2.46E-03	113815	6900	16.49	2.132E-03	0.00025	0.0005	0.004	123000	1.338E-03	289500	412500	0.0004	100	38
24/1 99	RØ4287	KK	Næ	ME1514	1.54	2.96E-03	148095	6949	21.31	2.470E-03	0.00025	0.0005	0.004	115000	1.260E-03	145500	260500	0.0004	100	22
25/1 99	RØ4219	KK	Nf	ME1514	1.54	2.96E-03	90535	4250	21.30	2.470E-03	0.00025	0.0005	0.004	115000	1.260E-03	145500	260500	0.0004	100	22
23/3 99	RØ2269	Kk	Nf	MZ1458	1.76	2.57E-03	149635	7393	20.24	2.122E-03	0.00025	0.0005	0.004	123000	1.211E-03	253500	376500	0.0004	100	30
31/1 99	RØ1529	Kh	Kb	MZ1458	1.65	2.80E-03	110200	5624	19.59	2.372E-03	0.00025	0.0005	0.004	123000	1.270E-03	181500	304500	0.0004	100	26
31/1 99	RØ2216	Næ	Kk	Me1508	1.54	2.96E-03	148095	6949	21.31	2.470E-03	0.00025	0.0005	0.004	115000	1.260E-03	145500	260500	0.0004	100	22
31/1 99	RØ2225	Kk	Næ	Me1508	1.54	2.96E-03	148095	6949	21.31	2.470E-03	0.00025	0.0005	0.004	115000	1.260E-03	145500	260500	0.0004	100	22
25/1 99	RØ4280	Næ	Kk	ME1514	1.54	2.96E-03	148095	6949	21.31	2.470E-03	0.00025	0.0005	0.004	115000	1.260E-03	145500	260500	0.0004	100	22
25/1 99	RØ2260	Nf	Kk	ME1514	1.76	2.80E-03	185526	6900	26.89	2.094E-03	0.00025	0.0005	0.004	115000	1.229E-03	253500	368500	0.0004	100	30
2/2 99	RØ4238	Næ	Kk	ME1508	1.54	2.96E-03	148095	6949	21.31	2.470E-03	0.00025	0.0005	0.004	115000	1.260E-03	145500	260500	0.0004	100	22
2/2 99	RØ4239	Kk	Næ	ME1508	1.54	2.96E-03	148095	6949	21.31	2.470E-03	0.00025	0.0005	0.004	115000	1.260E-03	145500	260500	0.0004	100	22
2/2 99	RØ2252	Nf	Kk	ME1508	1.76	2.80E-03	185526	6900	26.89	2.094E-03	0.00025	0.0005	0.004	115000	1.229E-03	253500	368500	0.0004	100	30
31/1 99	RØ2241	Kk	Nf	ME1508	1.54	2.96E-03	148095	6949	21.31	2.470E-03	0.00025	0.0005	0.004	115000	1.260E-03	145500	260500	0.0004	100	22
25/9 99	RØ5577	Kk	Kb	MZ1458	1.43	2.98E-03	113835	7184	15.85	2.676E-03	0.00025	0.0005	0.004	123000	1.188E-03	109500	232500	0.0004	100	18
25/9 99	RØ5568	Kb	Kk	MZ1458	1.43	2.98E-03	113835	7184	15.85	2.676E-03	0.00025	0.0005	0.004	123000	1.188E-03	109500	232500	0.0004	100	18
24/5 99	RØ3072	Kh	Hg	MZ1457	1.87	2.51E-03	46145	2852	16.18	2.195E-03	0.00025	0.0005	0.004	123000	1.320E-03	253500	376500	0.0004	100	34
25/4 99	RØ3072	Kh	Hg	MZ1457	1.87	2.51E-03	46145	2852	16.18	2.195E-03	0.00025	0.0005	0.004	123000	1.320E-03	253500	376500	0.0004	100	34
4/12 99	Rø3062	Kh	Hg	Mz1456	1.76	2.80E-03	185526	6900	26.89	2.094E-03	0.00025	0.0005	0.004	115000	1.229E-03	253500	368500	0.0004	100	30
4/12 99	Rø3062	Hg	Kh	Mz1456	1.76	2.80E-03	185526	6900	26.89	2.094E-03	0.00025	0.0005	0.004	115000	1.229E-03	253500	368500	0.0004	100	30

Dato	Togløb	Fra	Til	Lokomotiv	C_L	C_R	x (m)	t (s)	v_{snit}	C_0	C_1	C_2	f_{SL}	m_L	f_{SV}	m_V	m_{tog}	c_{SV}	F_{a1}	n_{ax}
7/10 99	GS7499	Gb	Rg	me1506	6.00	2.58E-03	62690	3840	16.33	2.080E-03	0.0005	0.0006	0.004	115000	1.823E-03	858880	973880	0.0006	100	117
7/10 99	GS7499	Rg	Fa	me1506	10.00	3.05E-03	156640	6420	24.40	2.145E-03	0.0005	0.0006	0.004	115000	1.792E-03	602880	717880	0.0006	100	84
7/10 99	GS7499	Fa	Ar	me1506	5.20	3.17E-03	107800	4680	23.03	2.340E-03	0.0005	0.0006	0.004	115000	1.704E-03	300190	415190	0.0006	100	45
28/9 99	Gs7495	Gb	Rg	Me1534	6.00	2.54E-03	63870	4964	12.87	2.185E-03	0.0005	0.0006	0.004	115000	1.759E-03	491060	606060	0.0006	100	69
28/9 99	Gs7495	Rg	Fa	Me1534	6.00	2.89E-03	156250	7079	22.07	2.117E-03	0.0005	0.0006	0.004	115000	1.797E-03	676380	791380	0.0006	100	93
28/9 99	Gs7495	Fa	Ar	Me1534	6.00	3.40E-03	106450	3663	29.06	2.220E-03	0.0005	0.0006	0.004	115000	1.755E-03	440250	555250	0.0006	100	63
15/9 99	GS 7495	Gb	Rg	me1503	12.00	2.78E-03	62595	3451	18.14	2.195E-03	0.0005	0.0006	0.004	115000	1.768E-03	486440	601440	0.0006	100	69
15/9 99	GS 7495	Rg	Fa	me1503	10.00	2.78E-03	156540	8022	19.51	2.135E-03	0.0005	0.0006	0.004	115000	1.804E-03	646380	761380	0.0006	100	90
15/9 99	GS 7495	Fa	Ar	me1503	4.50	3.38E-03	107690	3796	28.37	2.239E-03	0.0005	0.0006	0.004	115000	1.752E-03	415560	530560	0.0006	100	60
4/5 99	GP7523	Gl	Fa	Me1505	2.15	3.14E-03	211570	7934	26.67	2.102E-03	0.0005	0.0006	0.004	115000	1.407E-03	314000	429000	0.0006	100	34
4/5 99	GP7523	Fa	Ar	Me1505	2.00	3.02E-03	108540	4448	24.40	2.122E-03	0.0005	0.0006	0.004	115000	1.364E-03	285000	400000	0.0006	100	30
4/5 99	GP7523	Ar	Tov	Me1505	1.55	2.28E-03	9535	2146	4.44	2.189E-03	0.0005	0.0006	0.004	115000	1.173E-03	205000	320000	0.0006	100	18
26/1 99	GP7516	Tov	Fa	Me1535	1.40	4.09E-03	115145	3766	30.57	2.813E-03	0.0005	0.0006	0.004	115000	1.295E-03	90000	205000	0.0006	100	14
26/1 99	GP7516	Fa	Gl	Me1535	2.30	3.07E-03	210785	7956	26.49	2.046E-03	0.0005	0.0006	0.004	115000	1.418E-03	358000	473000	0.0006	100	38
3/2 99	GP7506	Od	Gl	Me1521	1.70	3.19E-03	148495	4962	29.93	1.959E-03	0.0005	0.0006	0.004	115000	1.152E-03	291000	406000	0.0006	100	22
20/9 og 28/9 99	GP7504	Ar	Fa	Me1515/1534	2.00	3.41E-03	108460	3635	29.84	2.176E-03	0.0005	0.0006	0.004	115000	1.396E-03	268770	383770	0.0006	100	30
20/9 og 28/9 99	GP7504	Fa	Rg	Me1515/1534	1.85	3.56E-03	156675	5081	30.84	2.270E-03	0.0005	0.0006	0.004	115000	1.381E-03	223970	338970	0.0006	100	26
20/9 og 28/9 99	GP7504	Rg	Gl	Me1515/1534	1.70	3.33E-03	54770	2185	25.07	2.393E-03	0.0005	0.0006	0.004	115000	1.362E-03	179190	294190	0.0006	100	22
10/5 99	GP7502	Fa	Od	Me1505	2.60	2.85E-03	60090	2473	24.30	1.957E-03	0.0005	0.0006	0.004	115000	1.432E-03	448000	563000	0.0006	100	46
7/5 99	GP7502	Fa	Sg	ME1510	2.60	2.90E-03	156280	6218	25.13	1.957E-03	0.0005	0.0006	0.004	115000	1.432E-03	448000	563000	0.0006	100	46
7/5 99	GP7502	Sg	Gl	ME1510	2.60	2.17E-03	56450	6636	8.51	1.957E-03	0.0005	0.0006	0.004	115000	1.432E-03	448000	563000	0.0006	100	46

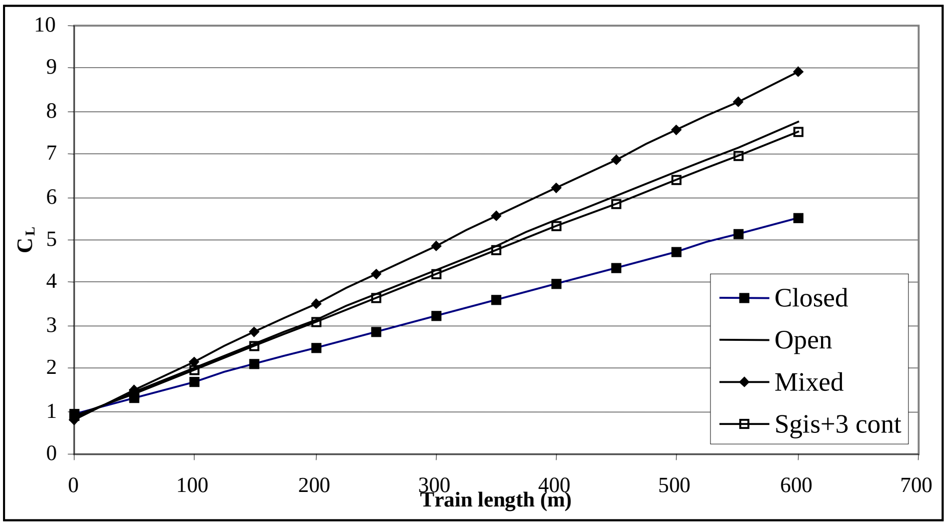
Dato	Togløb	Fra	Til	Lokomotiv	C_L	C_R	x (m)	t (s)	v_{snit}	C_0	C_1	C_2	f_{SL}	m_L	f_{SV}	m_V	m_{tog}	c_{SV}	F_{a1}	n_{AX}
25/1 99	GP7501Gl-Od	Gl	Od	Me1535	2.00	3.05E-03	148700	5621	26.45	2.033E-03	0.0005	0.0006	0.004	115000	1.312E-03	314000	429000	0.0006	100	30
25/1 99	GP7501 Od-Ar	Od	Ar	Me1535	2.15	3.07E-03	168555	6111	27.58	1.981E-03	0.0005	0.0006	0.004	115000	1.332E-03	358000	473000	0.0006	100	34
27/1 99	GP7291Rg-Od	Rg	Od	Me1535	2.90	2.97E-03	95825	3881	24.69	2.052E-03	0.0005	0.0006	0.004	115000	1.561E-03	457000	572000	0.0006	100	54
5/10 99	GP 7502	Gl	Fa	me1506	2.00	3.06E-03	117175	4860	24.11	2.176E-03	0.0005	0.0006	0.004	115000	1.396E-03	268780	383780	0.0006	100	30
5/10 99	GP 7502	Fa	Ar	me1506	4.30	2.85E-03	58675	2418	24.27	1.957E-03	0.0005	0.0006	0.004	115000	1.432E-03	447940	562940	0.0006	100	46
5/10 99	GP 7502	Ar	Tov	me1506	3.00	2.54E-03	103504	6367	16.26	2.045E-03	0.0005	0.0006	0.004	115000	1.417E-03	358380	473380	0.0006	100	38
24/2 99	G9521	GB	Kb	MZ1458	4.70	3.07E-03	108000	5151	20.97	2.353E-03	0.0005	0.0006	0.004	123000	1.468E-03	229000	352000	0.0006	100	30
26/2 99	G9521	GB	Kb	MZ1458	4.70	2.68E-03	108000	5161	20.93	1.959E-03	0.0005	0.0006	0.004	123000	1.356E-03	416000	539000	0.0006	100	40
1/3 99	G9464	Kj	Gb	MZ1457	6.70	1.90E-03	55465	3060	18.13	1.316E-03	0.0005	0.0006	0.004	123000	9.431E-04	886000	1009000	0.0006	100	34
25/2 99	G9425	Gb	Kj	MZ1457	7.40	2.10E-03	53000	3376	15.70	1.628E-03	0.0005	0.0006	0.004	123000	1.407E-03	1316360	1439360	0.0006	100	114
25/1 99	G9409	Gb	Kj	Me1508	7.50	1.58E-03	52430	3732	14.05	1.172E-03	0.0005	0.0006	0.004	115000	1.004E-03	1928000	2043000	0.0006	100	81
13/9 99	G9217	Gb	Rg	Me1508	12.00	2.18E-03	18025	1725	10.45	1.911E-03	0.0005	0.0006	0.004	115000	1.649E-03	914430	1029430	0.0006	100	106
13/9 99	G9217	Rg	Næ	Me1508	5.20	2.95E-03	26815	1555	17.24	2.405E-03	0.0005	0.0006	0.004	115000	2.140E-03	691850	806850	0.0006	100	122
13/9 99	G9217	Næ	Nf	Me1508	1.70	3.70E-03	55885	2925	19.11	3.070E-03	0.0005	0.0006	0.004	115000	1.581E-03	71790	186790	0.0006	100	18
20/9 99	G9217	Gb	Rg	Me1515	10.00	2.83E-03	62640	3153	19.87	2.166E-03	0.0005	0.0006	0.004	115000	1.972E-03	1087240	1202240	0.0006	100	162
20/9 99	G9217	Rg	Næ	Me1515	11.80	2.97E-03	26845	1294	20.75	2.260E-03	0.0005	0.0006	0.004	115000	2.001E-03	771670	886670	0.0006	100	122
20/9 99	G9217	Næ	Nf	Me1515	4.50	3.26E-03	55465	2971	18.67	2.656E-03	0.0005	0.0006	0.004	115000	1.784E-03	177390	292390	0.0006	100	34
27/1 99	G89106	Od	Rg	Me1535	6.00	3.11E-03	96000	4380	21.92	2.340E-03	0.0005	0.0006	0.004	115000	1.735E-03	315590	430590	0.0006	100	48
27/1 99	G89106	Rg	GB	Me1535	6.00	2.84E-03	62000	4029	15.39	2.376E-03	0.0005	0.0006	0.004	115000	1.697E-03	274880	389880	0.0006	100	42
8/2 99	G7515	Ar	Ab	Me1522	1.25	3.93E-03	142345	5721	24.88	3.001E-03	0.0005	0.0006	0.004	115000	1.173E-03	62800	177800	0.0006	100	10

Appendix 4 Air resistance goods grains as a function of train length

C_L as a function of train length based on Swedish wagon data.



C_L as a function of train length based on German wagon data.



Appendix 5 Station Abbreviations

Abbreviation	Station	Abbreviation	Station
Ab	Aalborg	Næ	Næstved
Ar	Århus H	Nf	Nykøbing Falster
Arb	Århus H (G)	Ng	Nyborg
Es	Esbjerg	Od	Odense
Fa	Fredericia	Os	Hornslet
Fh	Frederikshavn	Pa	Padborg
GB	Københavns Godsbanegård	Rd	Randers
Gl	Glostrup	Rg	Ringsted
Gr	Grenå	Ro	Roskilde
Hg	Helsingør	Sd	Skanderborg
Hr	Herning	Sdb	Sønderborg
Htå	Høje Tåstrup	So	Sorø
Kb	Kalundborg	Sg	Slagelse
Kd	Kolding	Sj	Skjern
Kgt	Kongsvang	Sl	Silkeborg
Kh	Københavns Hovedbanegård	Str	Struer
Kj	Køge	Ti	Thisted
Kk	Østerport	Tov	Torsøvej
Kø	Korsør	Val	Valby
Lg	Langå	Vg	Viborg

Appendix 6 Distances

København H - Sønderborg

Station	km	dx
Østerport	0	0
KBH	2.9	2.9
Høje Tåstrup	22.4	19.5
Roskilde	34.2	11.8
Ringsted	66.8	32.6
Slagelse	95.1	28.3
Korsør	111.2	16.1
Nyborg	134.5	23.3
Odense	163.2	28.7
Holmstrup	171.8	8.6
Tommerup	178.4	6.6
Skalbjerg	181.7	3.3
Bred	184	2.3
Årup	187.6	3.6
Gelsted	193.1	5.5
Ejby	197.7	4.6
Karlslunde	207.2	9.5
Middelfart	213.3	6.1
Snoghøj	219.2	5.9
Fredericia	223.5	4.3
Kolding	243.4	19.9
Lunderskov	256.3	12.9
Vamdrup	262.3	6
Sommersted	275.3	13
Vojens	282.7	7.4
Rødekro	303.1	20.4
Tinglev	318.8	15.7
Kliplev	335.1	16.3
Gråsten	350.1	15
Sønderborg	360	9.9

København H - Århus

Station	km	dx
KBH	0.0	0.0
Høje Tåstrup	19.7	19.7
Roskilde	31.5	11.7
Ringsted	64.1	32.6
Slagelse	93.1	29.1
Korsør	108.5	15.4
Nyborg	131.7	23.3
Odense	160.5	28.7
Middelfart	210.4	49.9
Fredericia	220.7	10.3
Vejle	246.4	25.7
Horsens	277.8	31.4
Skanderborg	306.5	28.7
Århus H	329.1	22.6
Langå	375.0	46.0
Randers	388.4	13.4
Hobro	419.7	31.3
Aalborg	469.1	49.4
Hjørring	517.3	48.2
Frederikshavn	554.0	36.7

Station	km	dx
Århus-Skjern		
Århus	0	0
Skanderborg	22.6	22.6
Silkeborg	52.7	30.1
Ikast	82	29.3
Herning	93.8	11.8
Skjern	134.5	40.7

Fredericia-Esbjerg

Fredericia	0	0
Kolding	19.9	19.9
Lunderskov	32.8	32.8
Bramming	142.9	110.1
Esbjerg	246	103.1

Helsingør-København

Helsingør	0	0
Snekkersten	3.5	3.5
Espergærde	6.2	2.7
Humlebæk	9.9	3.7
Nivå	13.7	3.8
Kokkedal	17.1	3.4
Rungsted Kyst	20.1	3
Vedbæk	24.1	4
Skodsborg	27.4	3.3
Klampenborg	32.9	5.5
Hellerup	38.4	5.5
Østerport	43.3	4.9
Nørreport	44.7	1.4
KBH	46.2	1.5

Station	km	dx
Østerport-Kalundborg		
Østerport	0	0
KBH	2.9	2.9
Høje Tåstrup	22.4	19.5
Roskilde	34.2	11.8
Lejre	43.5	9.3
Tølløse	57.3	13.8
Holbæk	69.8	12.5
Kalundborg	113.3	43.5

Østerport-Nykøbing F.

Østerport	0	0
KBH	2.9	2.9
Høje Tåstrup	22.4	19.5
Roskilde	34.2	11.8
Ringsted	63.9	29.7
Næstved	90.7	26.8
Vordingborg	118.1	27.4
Nykøbing F.	146.9	28.8

Århus-Viborg-Thisted

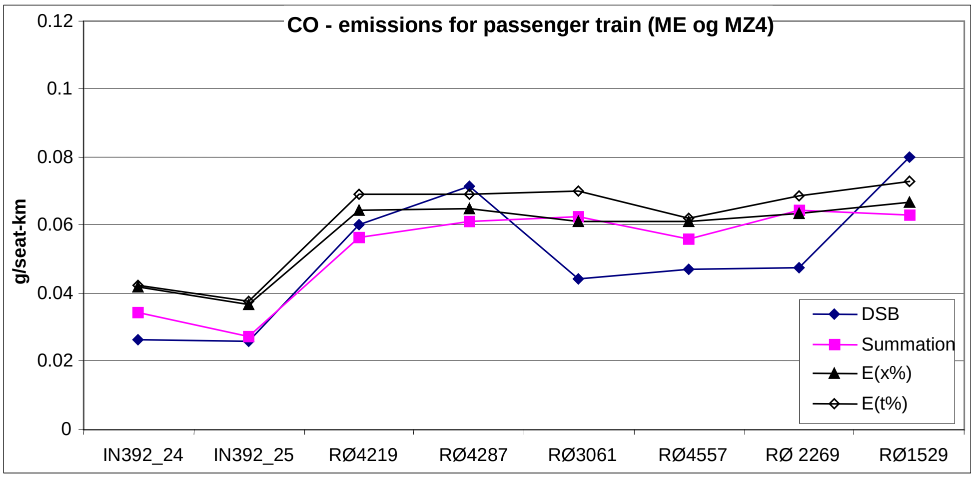
Århus	0	0
Langå	46	46
Viborg	86.2	40.2
Skive	116.5	30.3
Struer	148.4	31.9
Thisted	223.4	75

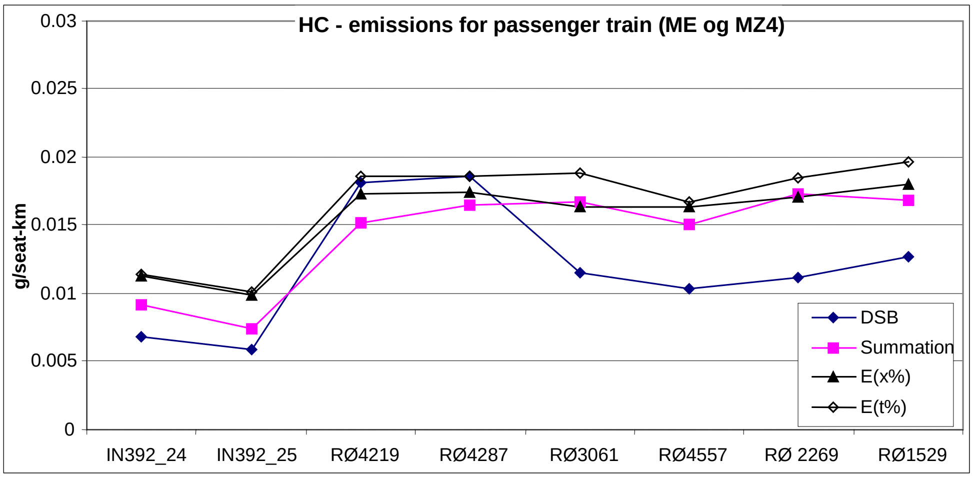
Appendix 7 Emissions from test simulations

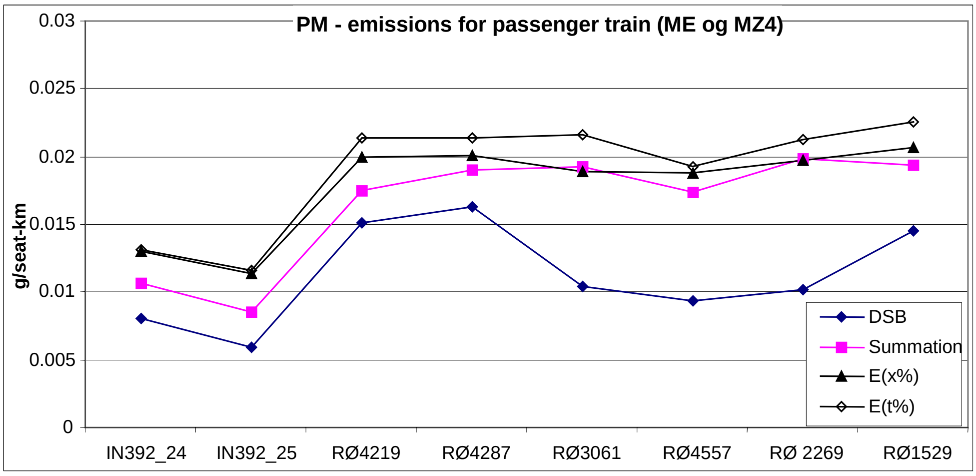
This appendix shows of CO, HC and PM from the test simulations in Chapter 8. Also included are the corresponding values from DSB's calculations.

SO_2 is not shown, since DSB has only calculated this type of emission for a few runs.

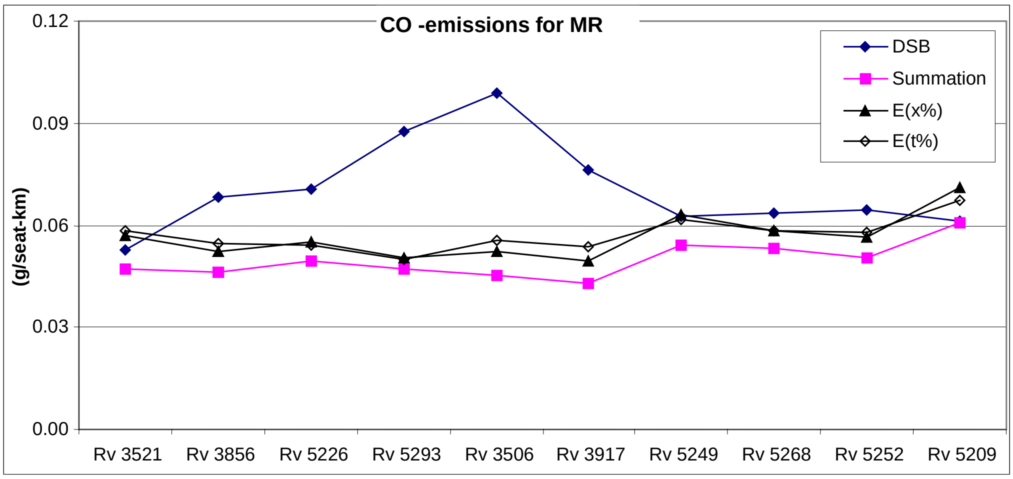
Locomotive powered passenger train:

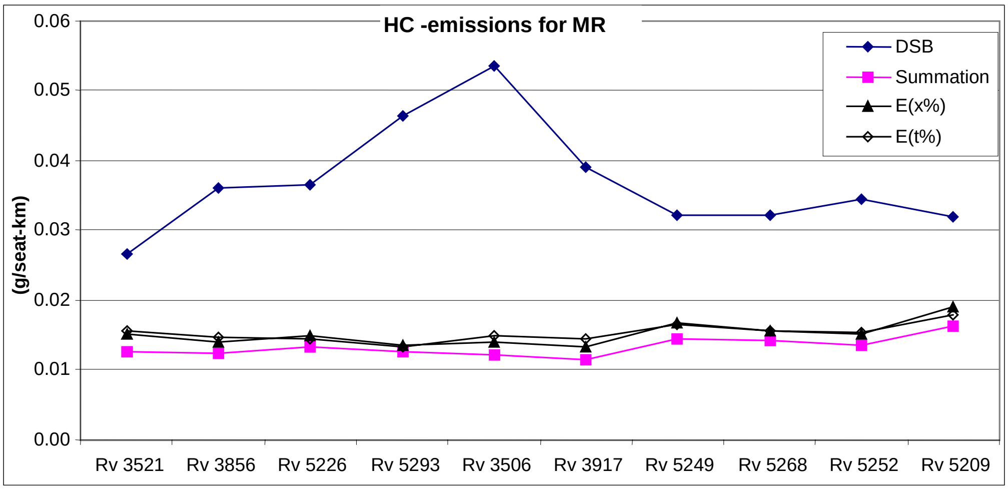


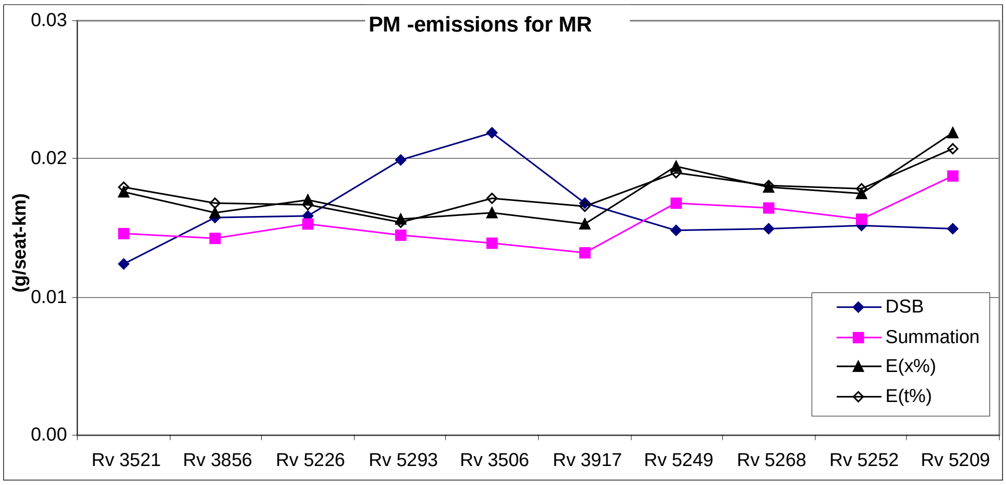




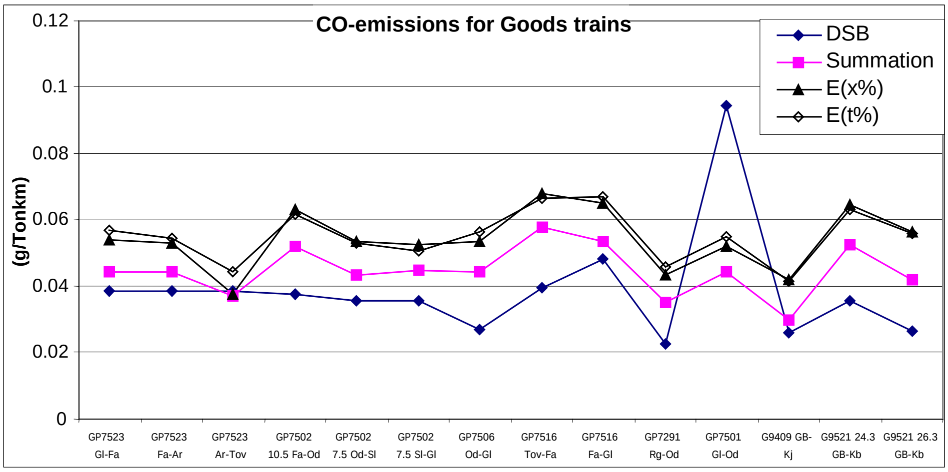
Emissions from MR train

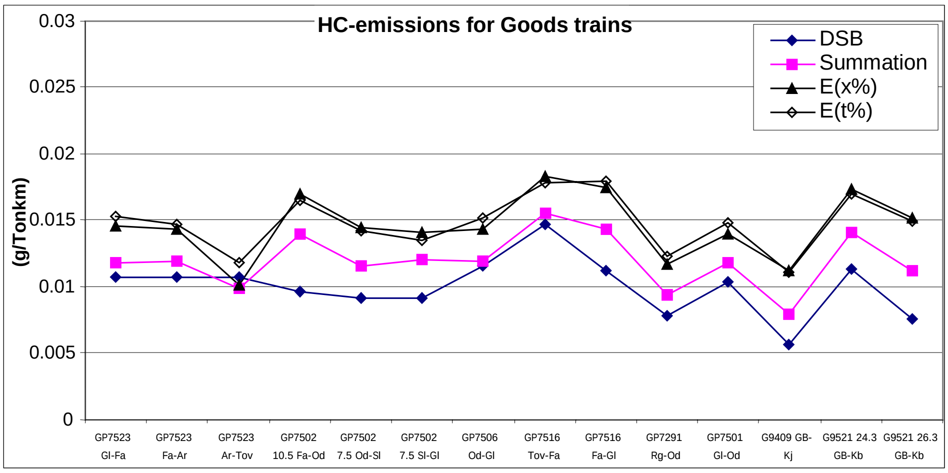

CO -emissions for MR
(g/seat-km)
0.12
0.09
0.06
0.03
0.00
DSB
Summation
E(x%)
E(t%)
Rv 3521
Rv 3856
Rv 5226
Rv 5293
Rv 3506
Rv 3917
Rv 5249
Rv 5268
Rv 5252
Rv 5209

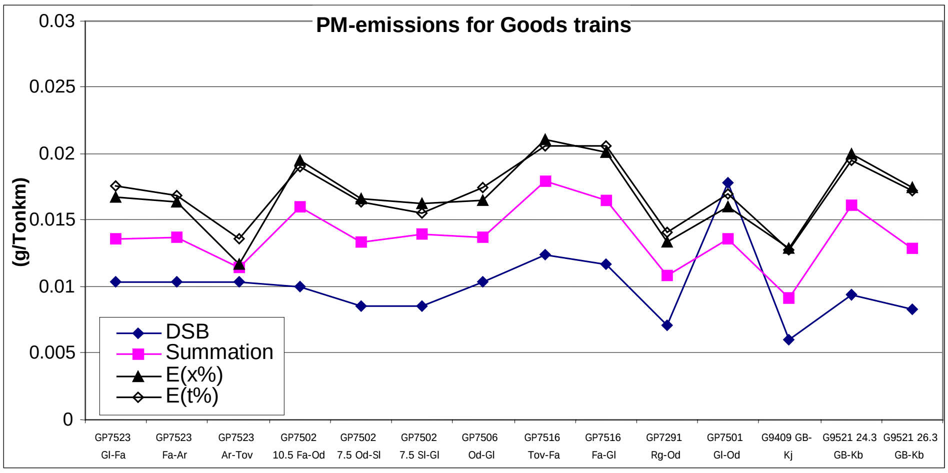

HC -emissions for MR
(g/seat-km)
0.06
0.05
0.04
0.03
0.02
0.01
0.00
DSB
Summation
E(x%)
E(t%)
Rv 3521
Rv 3856
Rv 5226
Rv 5293
Rv 3506
Rv 3917
Rv 5249
Rv 5268
Rv 5252
Rv 5209


PM -emissions for MR
(g/seat-km)
0.03
0.02
0.01
0.00
DSB
Summation
E(x%)
E(t%)
Rv 3521
Rv 3856
Rv 5226
Rv 5293
Rv 3506
Rv 3917
Rv 5249
Rv 5268
Rv 5252
Rv 5209

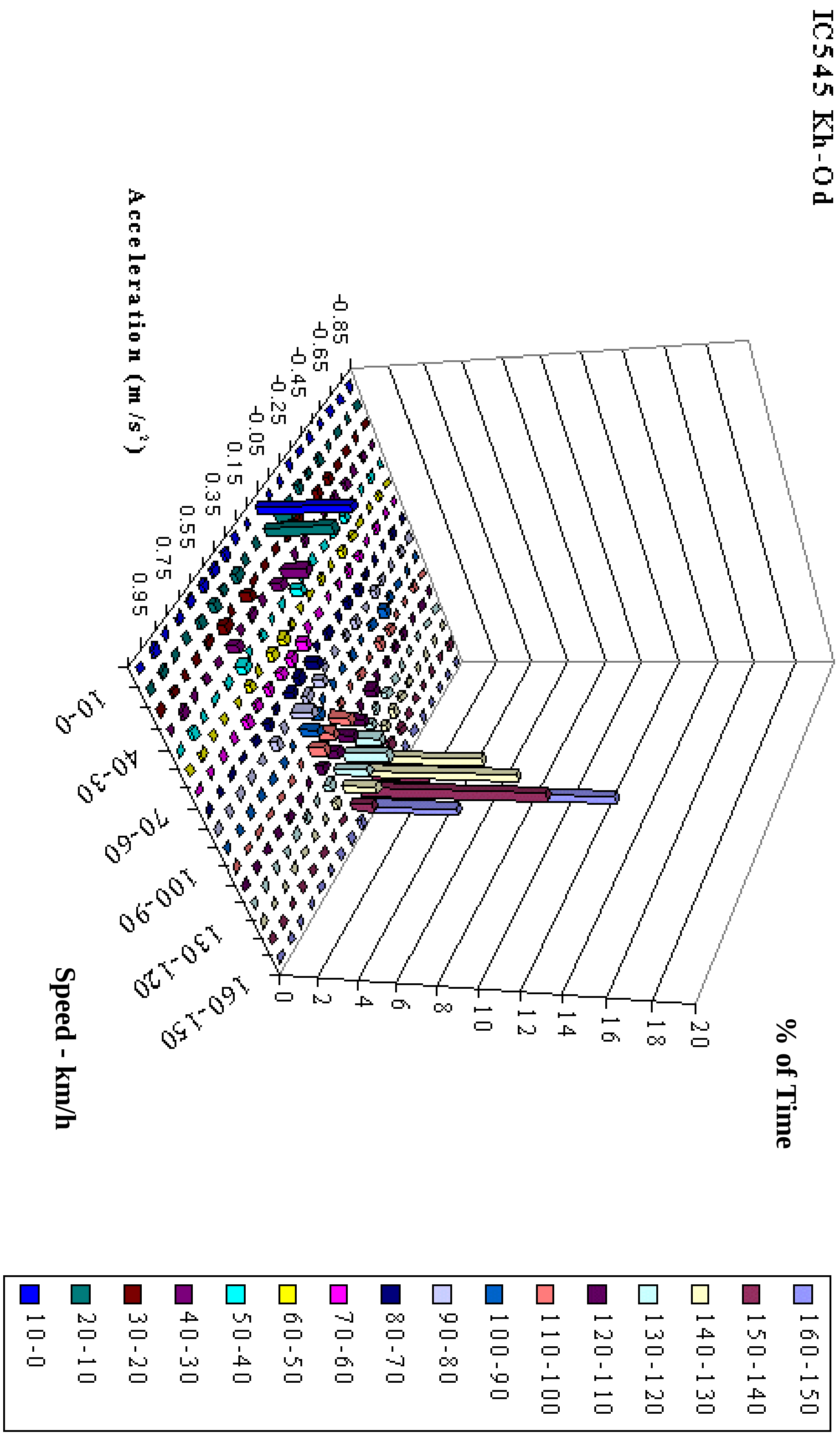
Emissions for goods train



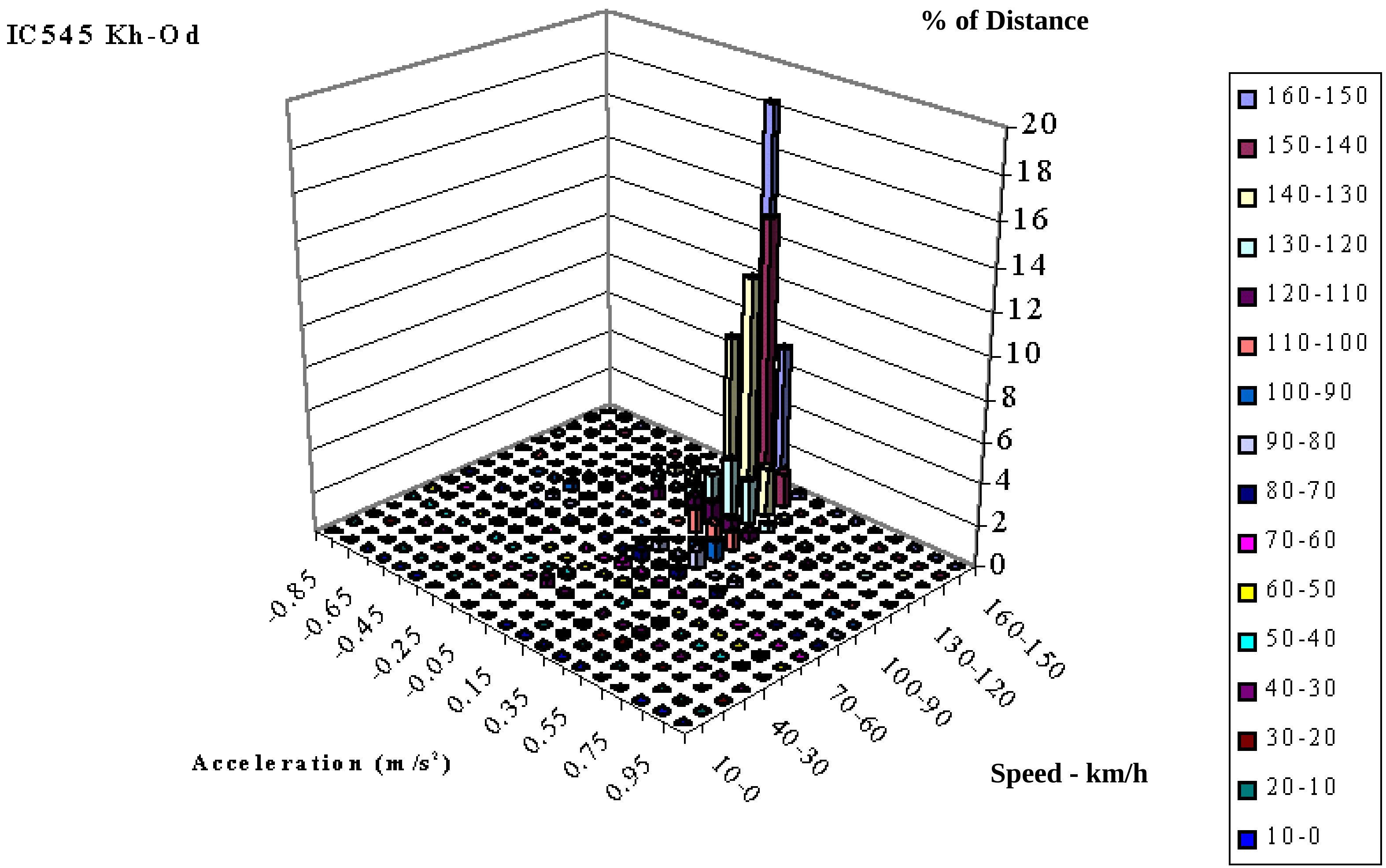




Appendix 8 Driving distribution for IC545. Kh-Od

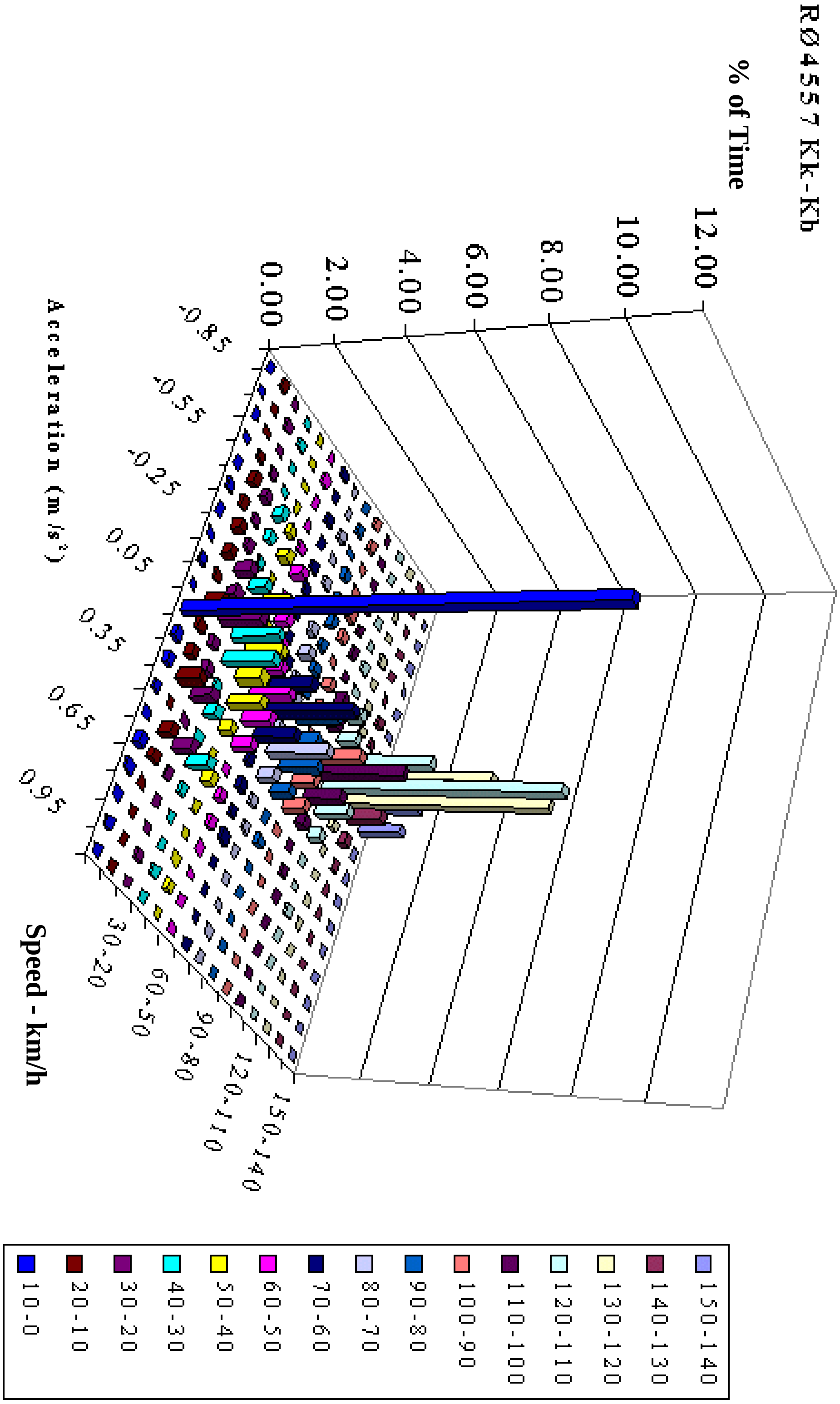


Tidsfordeling		Hastighedsinterval															
IC545		160-150	150-140	140-130	130-120	120-110	110-100	100-90	90-80	80-70	70-60	60-50	50-40	40-30	30-20	20-10	10-0
a_{MAX}	a_{MIN}																
1.0	0.9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.9	0.8	0.00	0.00	0.00	0.00	0.02	0.02	0.04	0.02	0.00	0.00	0.11	0.15	0.17	0.11	0.06	0.18
0.8	0.7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.7	0.6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.11
0.6	0.5	0.00	0.00	0.00	0.00	0.11	0.02	0.04	0.00	0.11	0.26	0.11	0.06	0.02	0.07	0.22	0.07
0.5	0.4	0.00	0.04	0.00	0.09	0.07	0.04	0.11	0.33	0.33	0.17	0.29	0.52	0.59	0.48	0.33	0.22
0.4	0.3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.22	0.00	0.00	0.00	0.00	0.11	0.13
0.3	0.2	0.07	0.00	0.18	0.31	0.42	0.88	0.96	1.09	0.52	0.33	0.33	0.18	0.13	0.52	0.35	0.17
0.2	0.1	0.17	1.22	1.80	1.77	0.61	0.85	0.50	0.29	0.29	0.37	0.37	0.00	0.00	0.00	0.00	0.00
0.1	0.0	4.84	9.81	8.65	2.34	0.90	1.14	0.00	0.55	0.74	0.59	0.17	0.00	0.55	0.00	0.00	0.00
0.0	-0.1	12.48	3.11	6.42	1.47	0.98	0.04	0.00	0.00	0.00	0.00	0.00	0.61	1.36	0.00	3.59	4.93
-0.1	-0.2	0.26	0.31	0.48	0.53	0.11	0.00	0.00	0.00	0.18	0.00	0.00	0.00	0.06	0.18	0.92	0.00
-0.2	-0.3	0.09	0.17	0.33	0.13	0.53	0.15	0.07	0.18	0.11	0.00	0.11	0.00	0.11	0.26	0.07	0.00
-0.3	-0.4	0.00	0.28	0.29	0.33	0.00	0.00	0.00	0.22	0.22	0.06	0.00	0.11	0.00	0.09	0.17	0.00
-0.4	-0.5	0.00	0.07	0.17	0.13	0.15	0.22	0.13	0.13	0.26	0.09	0.26	0.18	0.07	0.20	0.07	0.00
-0.5	-0.6	0.00	0.04	0.04	0.04	0.06	0.29	0.42	0.28	0.06	0.18	0.22	0.26	0.15	0.24	0.13	0.00
-0.6	-0.7	0.06	0.00	0.00	0.00	0.07	0.04	0.11	0.04	0.06	0.00	0.00	0.00	0.22	0.09	0.00	0.00
-0.7	-0.8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.00	0.00	0.00	0.00	0.00	0.00
-0.8	-0.9	0.04	0.00	0.04	0.00	0.07	0.07	0.00	0.09	0.07	0.04	0.09	0.11	0.02	0.04	0.00	0.00
-0.9	-1.0	0.00	0.06	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.00

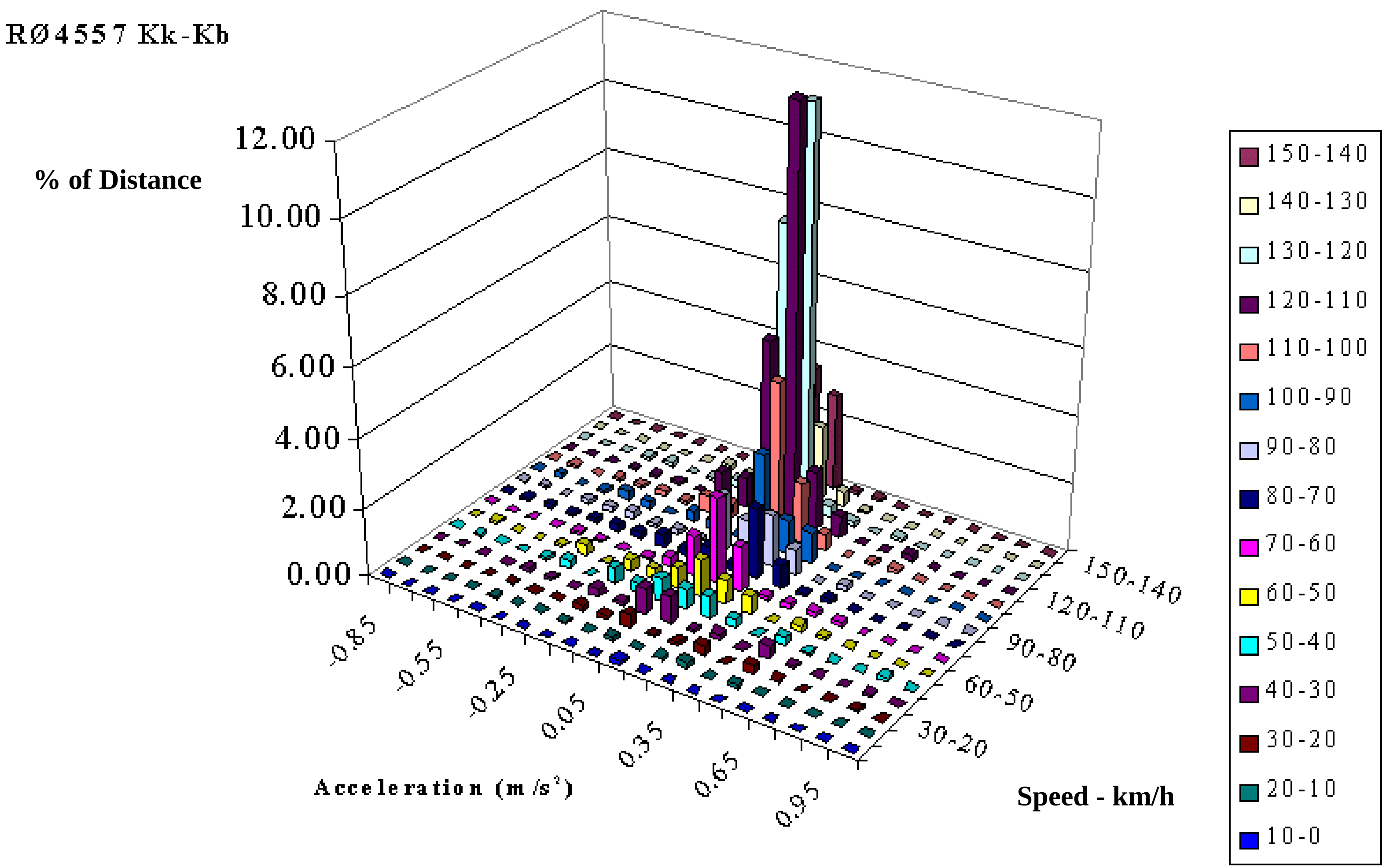

IC545 Kh-Od
% of Distance
0
2
4
6
8
10
12
14
16
18
20
-0.85
-0.65
-0.45
-0.25
-0.05
0.15
0.35
0.55
0.75
0.95
Acceleration (m/s²)
10-0
40-30
70-60
100-90
130-120
160-150
Speed - km/h
160-150
150-140
140-130
130-120
120-110
110-100
100-90
90-80
80-70
70-60
60-50
50-40
40-30
30-20
20-10
10-0

Stedsfordeling		Hastighedsinterval															
IC545		160-150	150-140	140-130	130-120	120-110	110-100	100-90	90-80	80-70	70-60	60-50	50-40	40-30	30-20	20-10	10-0
a_{MAX}	a_{MIN}																
1.0	0.9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.9	0.8	0.00	0.00	0.00	0.00	0.03	0.03	0.06	0.03	0.00	0.00	0.07	0.10	0.08	0.04	0.02	0.02
0.8	0.7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.7	0.6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.01
0.6	0.5	0.00	0.00	0.00	0.00	0.14	0.03	0.06	0.00	0.09	0.22	0.05	0.03	0.01	0.02	0.04	0.01
0.5	0.4	0.00	0.06	0.00	0.12	0.07	0.03	0.09	0.28	0.28	0.12	0.14	0.22	0.20	0.16	0.06	0.02
0.4	0.3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.12	0.00	0.00	0.00	0.00	0.02	0.02
0.3	0.2	0.12	0.00	0.25	0.37	0.45	0.87	0.87	0.93	0.37	0.22	0.18	0.07	0.04	0.12	0.07	0.02
0.2	0.1	0.25	1.68	2.37	2.18	0.65	0.84	0.47	0.22	0.22	0.22	0.22	0.00	0.00	0.00	0.00	0.00
0.1	0.0	7.17	13.71	11.28	2.80	1.06	1.18	0.00	0.44	0.53	0.37	0.09	0.00	0.19	0.00	0.00	0.00
0.0	-0.1	18.38	4.17	8.04	1.66	1.01	0.03	0.00	0.00	0.00	0.01	0.03	0.20	0.45	0.00	0.01	0.02
-0.1	-0.2	0.37	0.44	0.56	0.59	0.12	0.00	0.00	0.00	0.12	0.00	0.00	0.00	0.01	0.04	0.00	0.00
-0.2	-0.3	0.12	0.19	0.37	0.13	0.50	0.12	0.06	0.12	0.06	0.00	0.04	0.00	0.03	0.03	0.01	0.00
-0.3	-0.4	0.00	0.31	0.31	0.37	0.00	0.00	0.00	0.12	0.12	0.03	0.00	0.03	0.00	0.00	0.01	0.00
-0.4	-0.5	0.00	0.12	0.25	0.14	0.12	0.19	0.09	0.09	0.16	0.06	0.10	0.06	0.01	0.02	0.00	0.00
-0.5	-0.6	0.00	0.06	0.06	0.04	0.06	0.25	0.34	0.22	0.03	0.10	0.09	0.09	0.03	0.03	0.01	0.00
-0.6	-0.7	0.06	0.00	0.00	0.00	0.06	0.03	0.09	0.03	0.03	0.00	0.00	0.00	0.04	0.01	0.00	0.00
-0.7	-0.8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00
-0.8	-0.9	0.06	0.00	0.04	0.00	0.12	0.09	0.00	0.06	0.04	0.02	0.05	0.04	0.01	0.00	0.00	0.00
-0.9	-1.0	0.00	0.06	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Appendix 9 Driving distribution for RØ4557. Kh-Kb

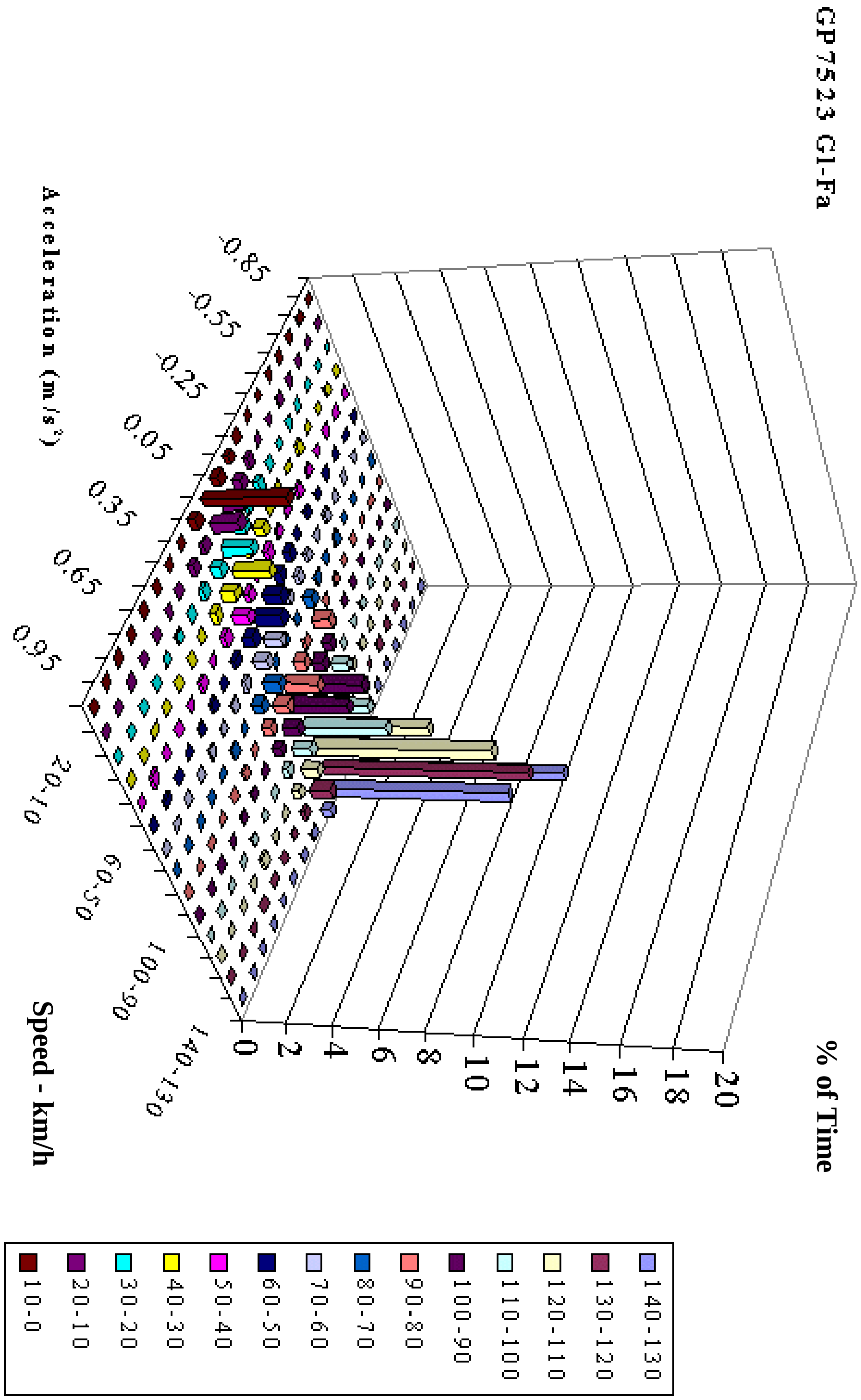


Tidsfordeling		Hastighedsinterval														
RØ4557		150-140	140-130	130-120	120-110	110-100	100-90	90-80	80-70	70-60	60-50	50-40	40-30	30-20	20-10	10-0
a_{MAX}	a_{MIN}															
1.0	0.9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.9	0.8	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.13	0.08	0.04	0.01	0.01
0.8	0.7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.7	0.6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
0.6	0.5	0.00	0.00	0.00	0.19	0.13	0.04	0.00	0.00	0.13	0.09	0.03	0.06	0.04	0.04	0.03
0.5	0.4	0.00	0.00	0.09	0.00	0.09	0.00	0.18	0.13	0.13	0.16	0.23	0.36	0.24	0.11	0.00
0.4	0.3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.13	0.00	0.00	0.00	0.00	0.00	0.00
0.3	0.2	0.09	0.09	0.09	0.66	0.44	0.88	0.75	0.66	0.13	0.50	0.24	0.18	0.25	0.18	0.02
0.2	0.1	0.09	0.44	0.35	1.76	1.76	1.01	1.54	2.06	1.32	0.70	0.67	0.04	0.09	0.05	0.02
0.1	0.0	2.81	2.20	11.72	12.31	4.53	2.72	1.14	0.18	2.55	1.09	0.59	0.79	0.05	0.03	0.14
0.0	-0.1	3.43	0.88	8.26	5.18	0.31	0.00	1.67	0.48	1.19	0.58	0.70	0.74	0.38	0.13	0.00
-0.1	-0.2	0.00	0.44	0.05	0.92	0.48	0.26	0.09	0.13	0.26	0.33	0.27	0.12	0.10	0.02	0.00
-0.2	-0.3	0.00	0.09	0.25	0.83	0.44	0.35	0.13	0.35	0.04	0.33	0.48	0.26	0.14	0.04	0.00
-0.3	-0.4	0.00	0.18	0.07	0.00	0.09	0.00	0.09	0.18	0.00	0.00	0.00	0.02	0.04	0.05	0.00
-0.4	-0.5	0.00	0.00	0.00	0.09	0.13	0.18	0.22	0.18	0.07	0.30	0.20	0.09	0.02	0.03	0.00
-0.5	-0.6	0.00	0.00	0.11	0.09	0.13	0.26	0.13	0.13	0.10	0.04	0.08	0.15	0.06	0.02	0.00
-0.6	-0.7	0.00	0.00	0.09	0.04	0.13	0.04	0.13	0.04	0.04	0.00	0.00	0.00	0.02	0.01	0.00
-0.7	-0.8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.04	0.00	0.00	0.00	0.00	0.00	0.00
-0.8	-0.9	0.00	0.00	0.00	0.00	0.04	0.13	0.09	0.09	0.00	0.07	0.03	0.04	0.03	0.00	0.00
-0.9	-1.0	0.00	0.00	0.00	0.00	0.00	0.04	0.04	0.00	0.06	0.00	0.00	0.00	0.00	0.01	0.00


RØ4557 Kk-Kb
% of Distance
12.00
10.00
8.00
6.00
4.00
2.00
0.00
-0.85
-0.55
-0.25
0.05
0.35
0.65
0.95
Acceleration (m/s²)
30-20
60-50
90-80
120-110
150-140
Speed - km/h
150-140
140-130
130-120
120-110
110-100
100-90
90-80
80-70
70-60
60-50
50-40
40-30
30-20
20-10
10-0

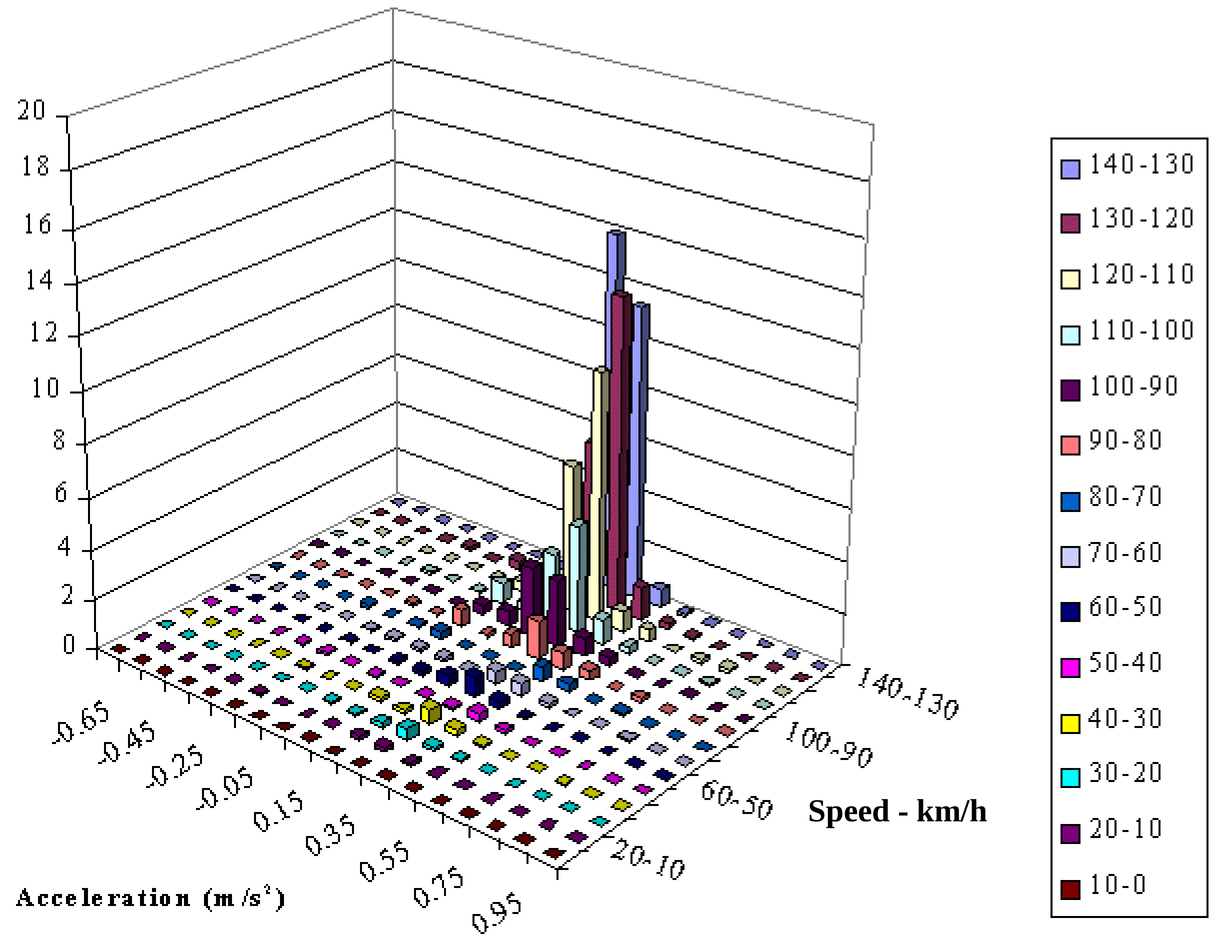
Stedsfordeling		Hastighedsinterval														
RØ4557		150-140	140-130	130-120	120-110	110-100	100-90	90-80	80-70	70-60	60-50	50-40	40-30	30-20	20-10	10-0
a_{MAX}	a_{MIN}															
1.0	0.9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.9	0.8	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.13	0.10	0.06	0.02	0.06
0.8	0.7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.7	0.6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10
0.6	0.5	0.00	0.00	0.00	0.08	0.05	0.02	0.00	0.00	0.10	0.13	0.05	0.11	0.08	0.16	0.19
0.5	0.4	0.00	0.00	0.03	0.00	0.06	0.00	0.13	0.10	0.11	0.19	0.32	0.65	0.55	0.39	0.00
0.4	0.3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.15	0.00	0.00	0.00	0.00	0.00	0.05
0.3	0.2	0.03	0.03	0.05	0.36	0.26	0.63	0.55	0.52	0.13	0.60	0.39	0.34	0.63	0.70	0.18
0.2	0.1	0.05	0.21	0.19	1.02	1.13	0.70	1.16	1.83	1.24	0.91	1.00	0.06	0.24	0.21	0.13
0.1	0.0	1.29	1.07	6.37	7.06	2.78	1.87	0.92	0.16	2.73	1.23	0.79	1.52	0.13	0.13	19.49
0.0	-0.1	1.63	0.42	4.51	3.05	0.19	0.00	1.34	0.40	1.29	0.73	1.12	1.44	1.28	0.55	0.00
-0.1	-0.2	0.00	0.23	0.03	0.58	0.34	0.19	0.08	0.15	0.27	0.48	0.42	0.24	0.31	0.10	0.03
-0.2	-0.3	0.00	0.05	0.15	0.50	0.31	0.27	0.11	0.34	0.03	0.44	0.82	0.55	0.50	0.27	0.00
-0.3	-0.4	0.00	0.10	0.05	0.00	0.05	0.00	0.10	0.19	0.00	0.00	0.00	0.05	0.11	0.31	0.00
-0.4	-0.5	0.00	0.00	0.00	0.06	0.10	0.13	0.18	0.18	0.06	0.39	0.32	0.16	0.06	0.10	0.08
-0.5	-0.6	0.00	0.00	0.06	0.05	0.08	0.19	0.11	0.10	0.10	0.05	0.15	0.31	0.18	0.23	0.00
-0.6	-0.7	0.00	0.00	0.03	0.03	0.10	0.03	0.11	0.03	0.03	0.00	0.00	0.00	0.06	0.08	0.00
-0.7	-0.8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.05	0.00	0.00	0.00	0.00	0.00	0.05
-0.8	-0.9	0.00	0.00	0.00	0.00	0.03	0.10	0.06	0.06	0.00	0.08	0.03	0.08	0.06	0.00	0.00
-0.9	-1.0	0.00	0.00	0.00	0.00	0.00	0.03	0.03	0.00	0.06	0.00	0.00	0.00	0.00	0.08	0.00

Appendix 10 Driving Distribution for GP7523. Gl-Fa



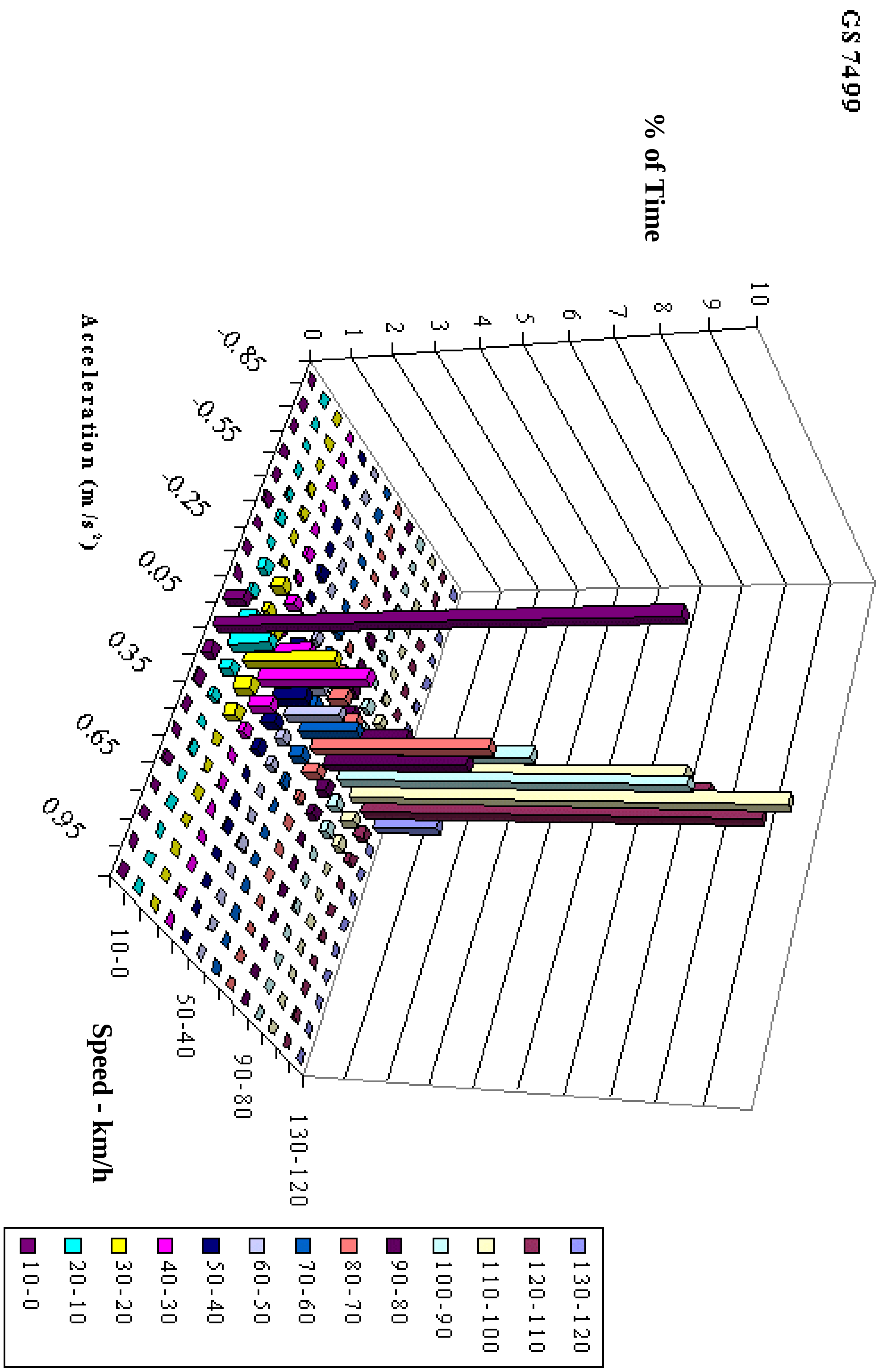
Tidsfordeling		Hastighedinterval													
GP7523		140-130	130-120	120-110	110-100	100-90	90-80	80-70	70-60	60-50	50-40	40-30	30-20	20-10	10-0
a_{MAX}	a_{MIN}														
1.0	0.9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03
0.9	0.8	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.06	0.03	0.04	0.04	0.01	0.03
0.8	0.7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.7	0.6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03
0.6	0.5	0.00	0.00	0.13	0.05	0.06	0.01	0.00	0.05	0.06	0.01	0.04	0.00	0.03	0.01
0.5	0.4	0.00	0.00	0.08	0.03	0.03	0.13	0.13	0.08	0.10	0.10	0.03	0.03	0.03	0.00
0.4	0.3	0.04	0.04	0.00	0.00	0.00	0.00	0.00	0.08	0.00	0.00	0.00	0.00	0.00	0.00
0.3	0.2	0.08	0.15	0.35	0.26	0.37	0.38	0.43	0.14	0.15	0.21	0.29	0.16	0.21	0.09
0.2	0.1	0.49	0.91	0.69	0.84	0.72	0.72	0.77	0.67	0.50	0.77	0.60	0.45	0.19	0.29
0.1	0.0	8.14	9.42	8.17	3.86	2.53	1.58	0.00	0.78	1.29	0.32	1.65	1.31	1.24	3.81
0.0	-0.1	10.26	4.88	4.92	2.57	2.79	0.57	0.00	0.08	0.81	0.10	0.30	0.49	0.88	0.34
-0.1	-0.2	0.82	0.28	0.81	0.42	0.52	0.09	0.06	0.21	0.33	0.20	0.44	0.16	0.37	0.29
-0.2	-0.3	0.00	0.06	0.32	0.74	0.42	0.78	0.43	0.21	0.26	0.14	0.09	0.23	0.18	0.00
-0.3	-0.4	0.04	0.30	0.08	0.04	0.00	0.08	0.15	0.15	0.00	0.04	0.00	0.08	0.00	0.00
-0.4	-0.5	0.00	0.00	0.10	0.08	0.08	0.13	0.05	0.04	0.10	0.15	0.03	0.03	0.03	0.00
-0.5	-0.6	0.00	0.11	0.01	0.05	0.03	0.03	0.15	0.10	0.05	0.13	0.11	0.03	0.10	0.00
-0.6	-0.7	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-0.7	-0.8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-0.8	-0.9	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.03	0.01	0.00	0.06
-0.9	-1.0	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00

GP7523 Gl-Fa


% of Distance
0
2
4
6
8
10
12
14
16
18
20
-0.65
-0.45
-0.25
-0.05
0.15
0.35
0.55
0.75
0.95
Acceleration (m/s²)
20-10
60-50
100-90
140-130
Speed - km/h
140-130
130-120
120-110
110-100
100-90
90-80
80-70
70-60
60-50
50-40
40-30
30-20
20-10
10-0

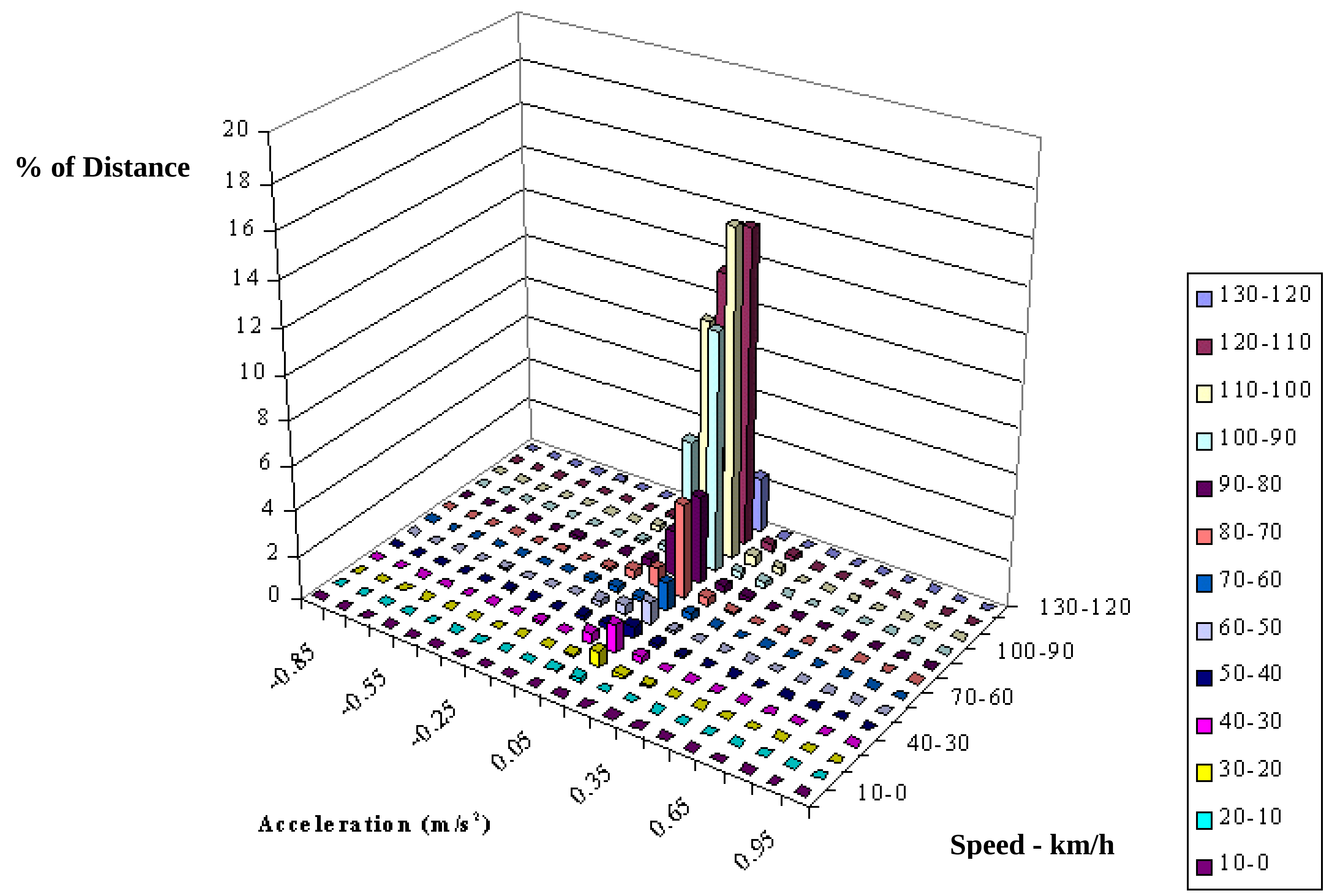
Stedsfordeling		Hastighedinterval													
GP7523		140-130	130-120	120-110	110-100	100-90	90-80	80-70	70-60	60-50	50-40	40-30	30-20	20-10	10-0
a_{MAX}	a_{MIN}														
1.0	0.9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.9	0.8	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.04	0.01	0.02	0.01	0.00	0.00
0.8	0.7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.7	0.6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.6	0.5	0.00	0.00	0.17	0.09	0.07	0.02	0.00	0.05	0.03	0.00	0.01	0.00	0.00	0.00
0.5	0.4	0.00	0.00	0.08	0.02	0.02	0.12	0.12	0.07	0.06	0.05	0.01	0.01	0.00	0.00
0.4	0.3	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.00
0.3	0.2	0.09	0.19	0.47	0.31	0.35	0.35	0.35	0.09	0.09	0.11	0.11	0.05	0.04	0.00
0.2	0.1	0.71	1.23	0.76	0.92	0.71	0.64	0.59	0.47	0.29	0.37	0.22	0.11	0.03	0.01
0.1	0.0	11.49	12.30	9.80	4.25	2.55	1.44	0.00	0.50	0.79	0.17	0.57	0.38	0.20	0.01
0.0	-0.1	13.99	6.24	5.79	2.77	2.72	0.50	0.00	0.05	0.42	0.05	0.09	0.14	0.14	0.01
-0.1	-0.2	1.13	0.34	0.90	0.43	0.50	0.07	0.05	0.14	0.17	0.09	0.14	0.03	0.05	0.01
-0.2	-0.3	0.00	0.07	0.38	0.78	0.40	0.66	0.31	0.14	0.12	0.05	0.03	0.05	0.02	0.00
-0.3	-0.4	0.05	0.37	0.09	0.05	0.00	0.05	0.09	0.09	0.00	0.01	0.00	0.02	0.00	0.00
-0.4	-0.5	0.00	0.00	0.09	0.07	0.07	0.12	0.05	0.02	0.06	0.08	0.01	0.00	0.00	0.00
-0.5	-0.6	0.00	0.18	0.02	0.07	0.02	0.02	0.14	0.06	0.03	0.05	0.04	0.00	0.01	0.00
-0.6	-0.7	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-0.7	-0.8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-0.8	-0.9	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.01	0.00	0.00	0.00
-0.9	-1.0	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Appendix 11 Driving Distribution for GS7499



Tidsfordeling		Hastighedsinterval												
GS7499		130-120	120-110	110-100	100-90	90-80	80-70	70-60	60-50	50-40	40-30	30-20	20-10	10-0
a_{MAX}	a_{MIN}													
1.0	0.9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.9	0.8	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.03	0.01	0.01	0.01	0.01	0.01
0.8	0.7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.7	0.6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.6	0.5	0.00	0.03	0.03	0.01	0.00	0.00	0.00	0.06	0.03	0.01	0.02	0.00	0.06
0.5	0.4	0.00	0.00	0.01	0.00	0.03	0.01	0.01	0.01	0.00	0.01	0.03	0.05	0.00
0.4	0.3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.3	0.2	0.00	0.12	0.16	0.19	0.16	0.12	0.07	0.13	0.14	0.16	0.30	0.10	0.08
0.2	0.1	0.02	0.27	0.32	0.23	0.27	0.39	0.32	0.18	0.35	0.56	0.40	0.30	0.18
0.1	0.0	1.57	9.24	10.35	8.08	3.39	4.19	1.40	1.31	0.83	2.57	2.13	0.97	14.19
0.0	-0.1	1.04	7.98	7.67	4.44	1.81	0.88	0.21	0.70	0.45	1.04	0.55	0.41	0.47
-0.1	-0.2	0.00	0.51	0.38	0.24	0.28	0.42	0.26	0.33	0.32	0.14	0.16	0.09	0.03
-0.2	-0.3	0.02	0.07	0.18	0.13	0.09	0.14	0.15	0.13	0.08	0.24	0.28	0.18	0.00
-0.3	-0.4	0.00	0.00	0.02	0.00	0.04	0.02	0.11	0.00	0.02	0.04	0.02	0.02	0.03
-0.4	-0.5	0.01	0.00	0.00	0.05	0.08	0.04	0.00	0.00	0.11	0.09	0.01	0.06	0.06
-0.5	-0.6	0.06	0.00	0.02	0.03	0.01	0.01	0.01	0.02	0.04	0.01	0.06	0.02	0.03
-0.6	-0.7	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.01	0.01	0.00
-0.7	-0.8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-0.8	-0.9	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.01	0.01	0.03	0.01	0.00	0.01
-0.9	-1.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

GS 7499



% of Distance
20
18
16
14
12
10
8
6
4
2
0
-0.85
-0.55
-0.25
0.05
0.35
0.65
0.95
Acceleration (m/s²)
130-120
100-90
70-60
40-30
10-0
Speed - km/h
130-120
120-110
110-100
100-90
90-80
80-70
70-60
60-50
50-40
40-30
30-20
20-10
10-0

Stedsfordeling		Hastighedsinterval												
GS7499		130-120	120-110	110-100	100-90	90-80	80-70	70-60	60-50	50-40	40-30	30-20	20-10	10-0
a_{MAX}	a_{MIN}													
1.0	0.9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.9	0.8	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.02	0.01	0.00	0.00	0.00	0.00
0.8	0.7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.7	0.6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.6	0.5	0.00	0.04	0.05	0.02	0.00	0.00	0.00	0.04	0.02	0.00	0.01	0.00	0.01
0.5	0.4	0.00	0.00	0.02	0.00	0.03	0.02	0.02	0.01	0.00	0.01	0.01	0.01	0.00
0.4	0.3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.3	0.2	0.00	0.23	0.26	0.24	0.20	0.14	0.06	0.09	0.09	0.08	0.11	0.03	0.01
0.2	0.1	0.03	0.37	0.43	0.29	0.31	0.40	0.29	0.13	0.20	0.27	0.13	0.07	0.02
0.1	0.0	2.54	14.32	14.86	10.85	3.99	4.22	1.26	1.01	0.53	1.25	0.73	0.19	0.06
0.0	-0.1	1.68	12.00	10.39	5.55	2.05	0.87	0.17	0.48	0.24	0.45	0.18	0.07	0.02
-0.1	-0.2	0.00	0.76	0.50	0.31	0.31	0.40	0.22	0.23	0.18	0.06	0.05	0.02	0.00
-0.2	-0.3	0.03	0.11	0.26	0.15	0.11	0.12	0.13	0.09	0.04	0.11	0.08	0.03	0.00
-0.3	-0.4	0.00	0.00	0.03	0.00	0.03	0.02	0.09	0.00	0.01	0.02	0.01	0.00	0.00
-0.4	-0.5	0.02	0.00	0.00	0.06	0.09	0.05	0.00	0.00	0.06	0.04	0.00	0.01	0.00
-0.5	-0.6	0.09	0.00	0.05	0.03	0.02	0.02	0.01	0.01	0.02	0.01	0.02	0.00	0.00
-0.6	-0.7	0.00	0.00	0.00	0.02	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-0.7	-0.8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-0.8	-0.9	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.00	0.00
-0.9	-1.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Appendix 12 Driving distribution for RØ3061, RØ3063 & IN392

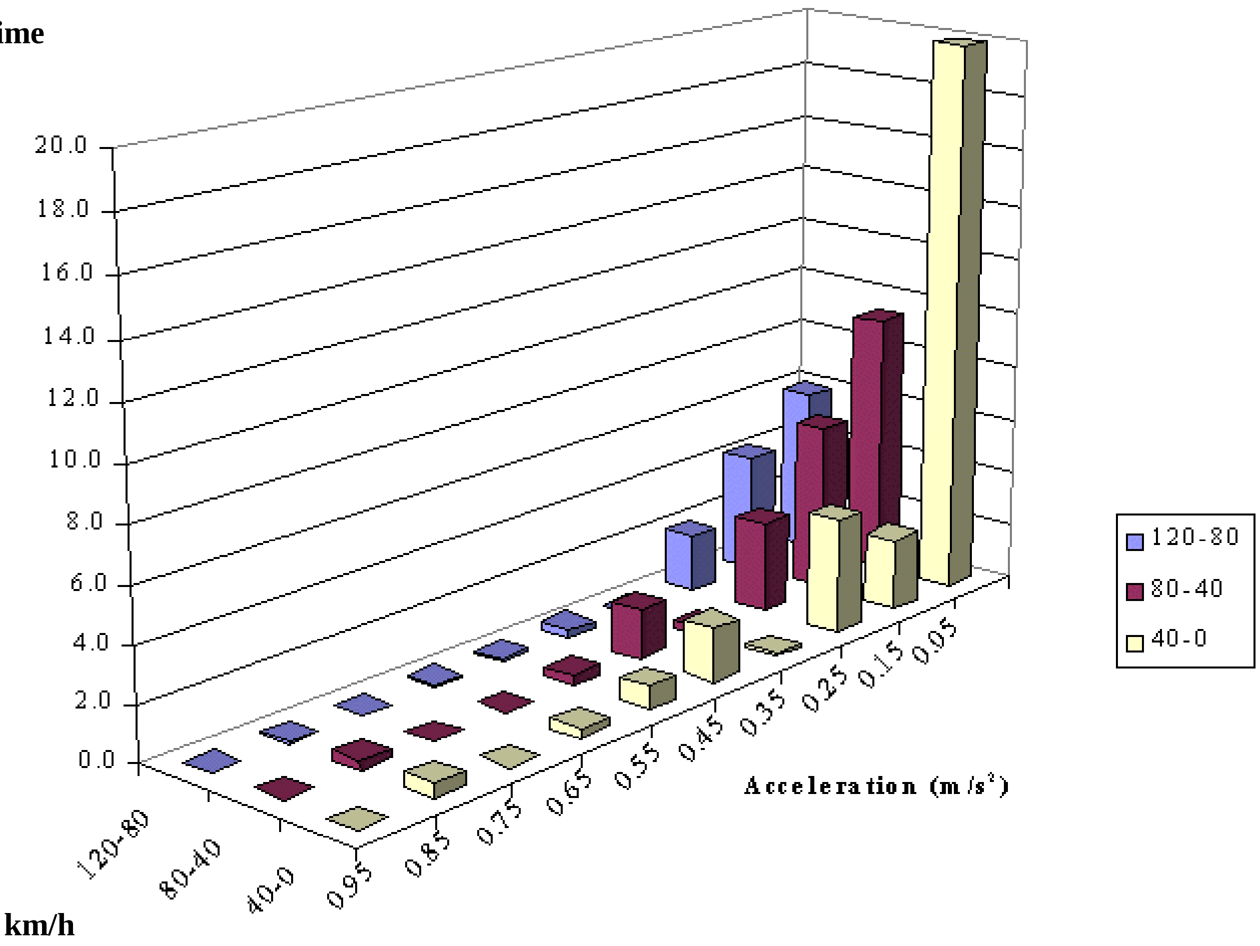
Temporal distribution		Spatial distribution

RØ3063											
a_{MAX}	**a_{MIN}**		**Speed interval**					**Speed interval**			
			120-80	*80-40*	*40-0*			*120-80*	*80-40*	*40-0*	
1	*0.9*		0.0	0.1	0.0			0.0	0.1	0.0	
0.9	*0.8*		0.1	0.3	0.5			0.2	0.5	0.4	
0.8	*0.7*		0.0	0.0	0.0			0.0	0.0	0.0	
0.7	*0.6*		0.1	0.0	0.3			0.2	0.0	0.1	
0.6	*0.5*		0.1	0.3	0.8			0.3	0.4	0.4	
0.5	*0.4*		0.3	1.8	2.0			0.5	2.7	1.3	
0.4	*0.3*		0.0	0.2	0.2			0.0	0.3	0.1	
0.3	*0.2*		2.1	3.3	4.1			4.7	4.4	2.3	
0.2	*0.1*		4.2	6.0	2.6			8.8	8.5	1.6	
0.1	*0*		6.0	9.4	26.1			12.8	12.8	1.6	

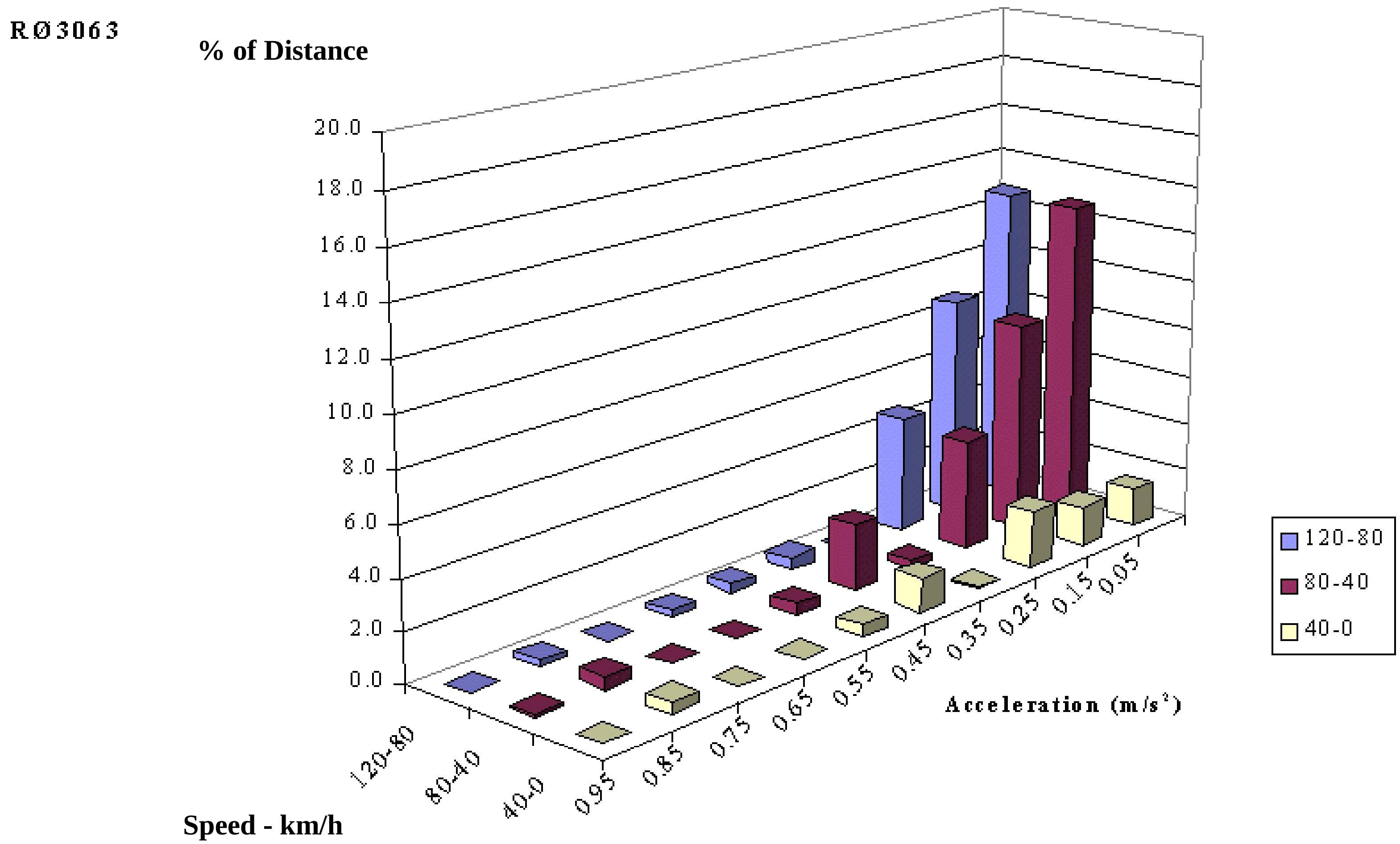
RØ3061											
a_{MAX}	**a_{MIN}**		**Speed interval**					**Speed interval**			
			150-100	*100-50*	*50-0*			*150-100*	*100-50*	*50-0*	
1	*0.9*		0	0	0			0	0	0	
0.9	*0.8*		0	0	0.2			0	0.1	0.2	
0.8	*0.7*		0	0	0			0	0	0	
0.7	*0.6*		0	0	0			0	0	0	
0.6	*0.5*		0	0.2	1			0	0.2	0.4	
0.5	*0.4*		0	1	1.7			0	1.5	0.8	
0.4	*0.3*		0	0.2	0.3			0	0.2	0.1	
0.3	*0.2*		0.4	2.7	4.4			0.8	3.8	2.4	
0.2	*0.1*		1.1	6.4	4.5			1.9	8.5	2.3	
0.1	*0*		1.5	16.2	13			2.9	21	2.7	

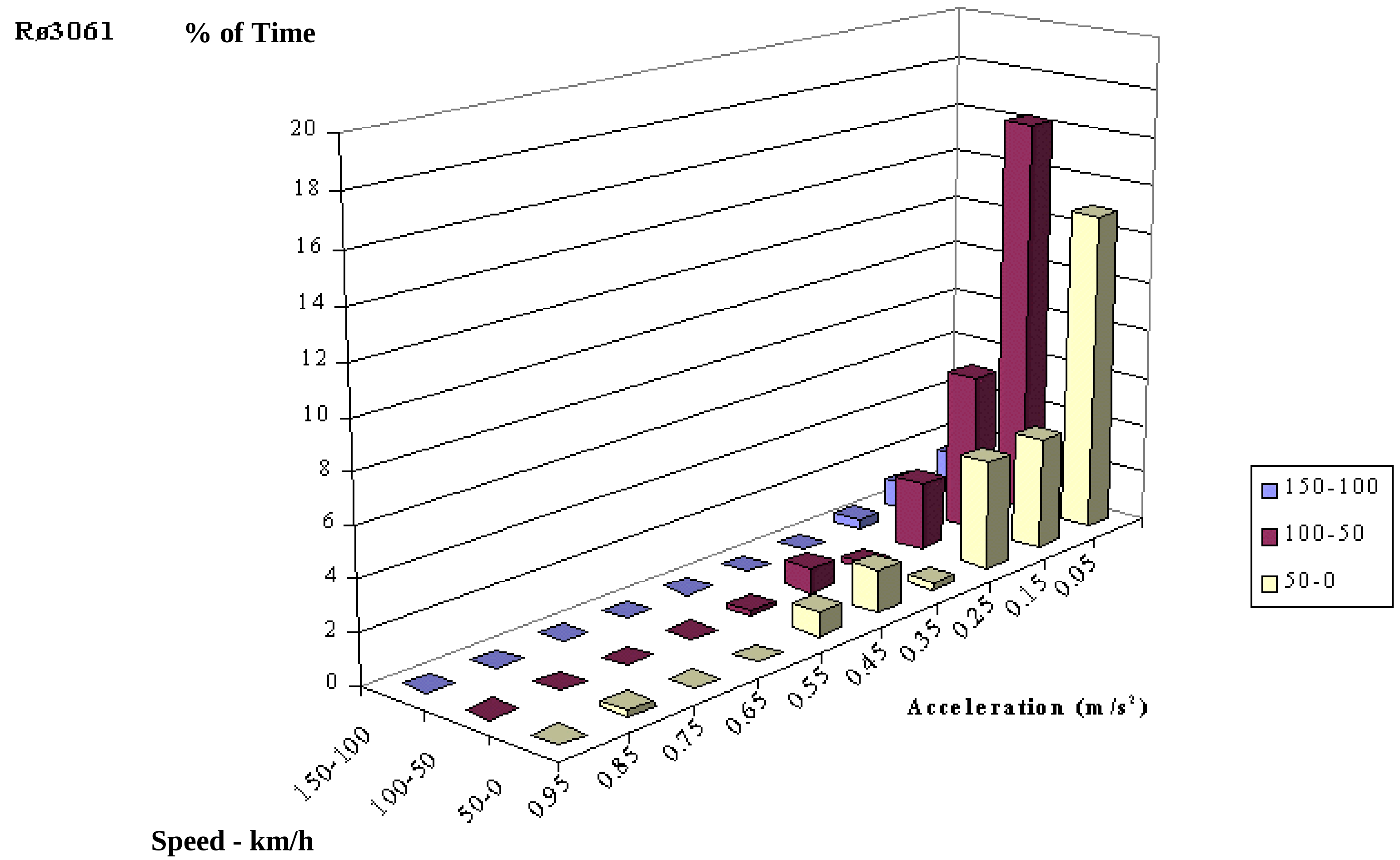
IN392											
a_{MAX}	**a_{MIN}**		**Speed interval**					**Speed interval**			
			140-105	*105-70*	*70-35*	*35-0*		*140-105*	*105-70*	*70-35*	*35-0*
1	*0.9*		0.0	0.0	0.0	0.0		0	0	0	0
0.9	*0.8*		0.0	0.0	0.1	0.0		0	0	0	0
0.8	*0.7*		0.0	0.0	0.0	0.0		0	0	0	0
0.7	*0.6*		0.0	0.0	0.0	0.0		0	0	0	0
0.6	*0.5*		0.1	0.0	0.2	0.3		0.1	0.1	0.1	0
0.5	*0.4*		0.0	0.0	0.3	0.0		0	0	0.2	0
0.4	*0.3*		0.0	0.0	0.0	0.0		0	0	0	0
0.3	*0.2*		0.7	1.0	0.4	0.8		1	1	0.2	0.3
0.2	*0.1*		1.1	2.3	1.5	1.3		1.4	2.4	0.9	0.4
0.1	*0*		19.5	15.5	5.5	6.8		27.3	16	3.4	2.4

RØ3063

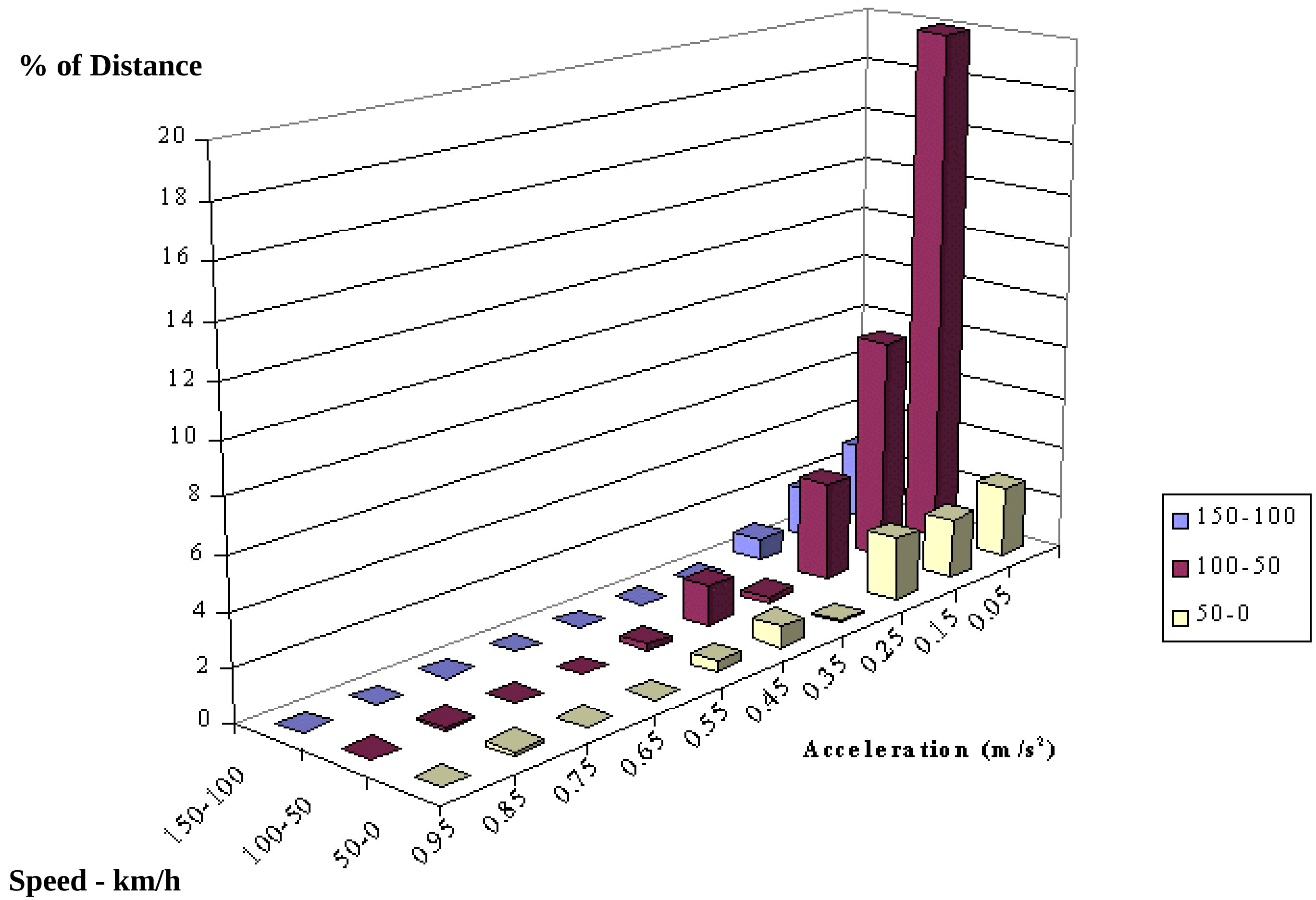


% of Time
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
120-80
80-40
40-0
Speed - km/h
0.95
0.85
0.75
0.65
0.55
0.45
0.35
0.25
0.15
0.05
Acceleration (m/s²)
120-80
80-40
40-0


RØ3063
% of Distance
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
120-80
80-40
40-0
0.95
0.85
0.75
0.65
0.55
0.45
0.35
0.25
0.15
0.05
Acceleration (m/s²)
Speed - km/h
120-80
80-40
40-0

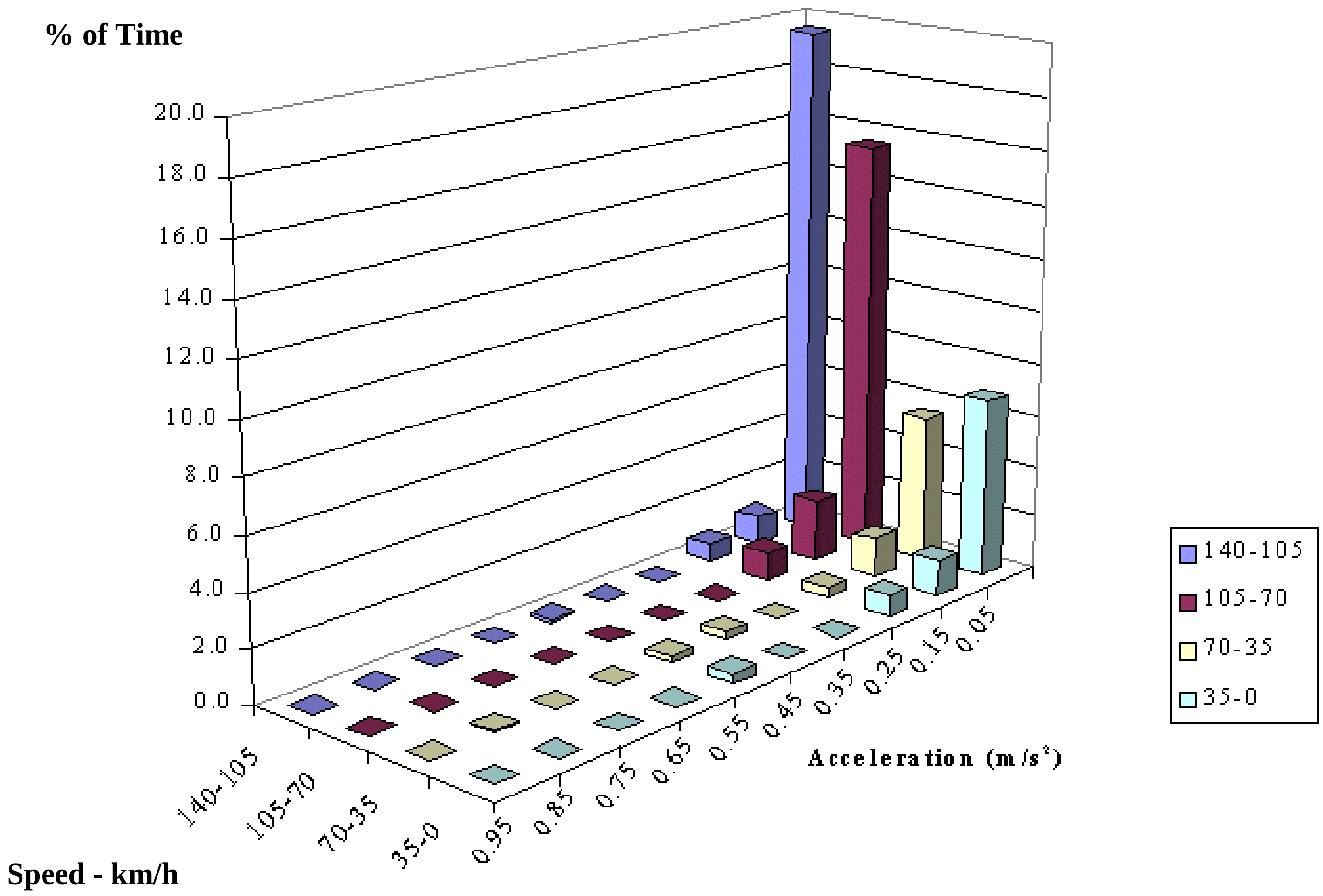

Rø3061
% of Time
20
18
16
14
12
10
8
6
4
2
0
150-100
100-50
50-0
Speed - km/h
0.95
0.85
0.75
0.65
0.55
0.45
0.35
0.25
0.15
0.05
Acceleration (m/s²)
150-100
100-50
50-0

Rø3061

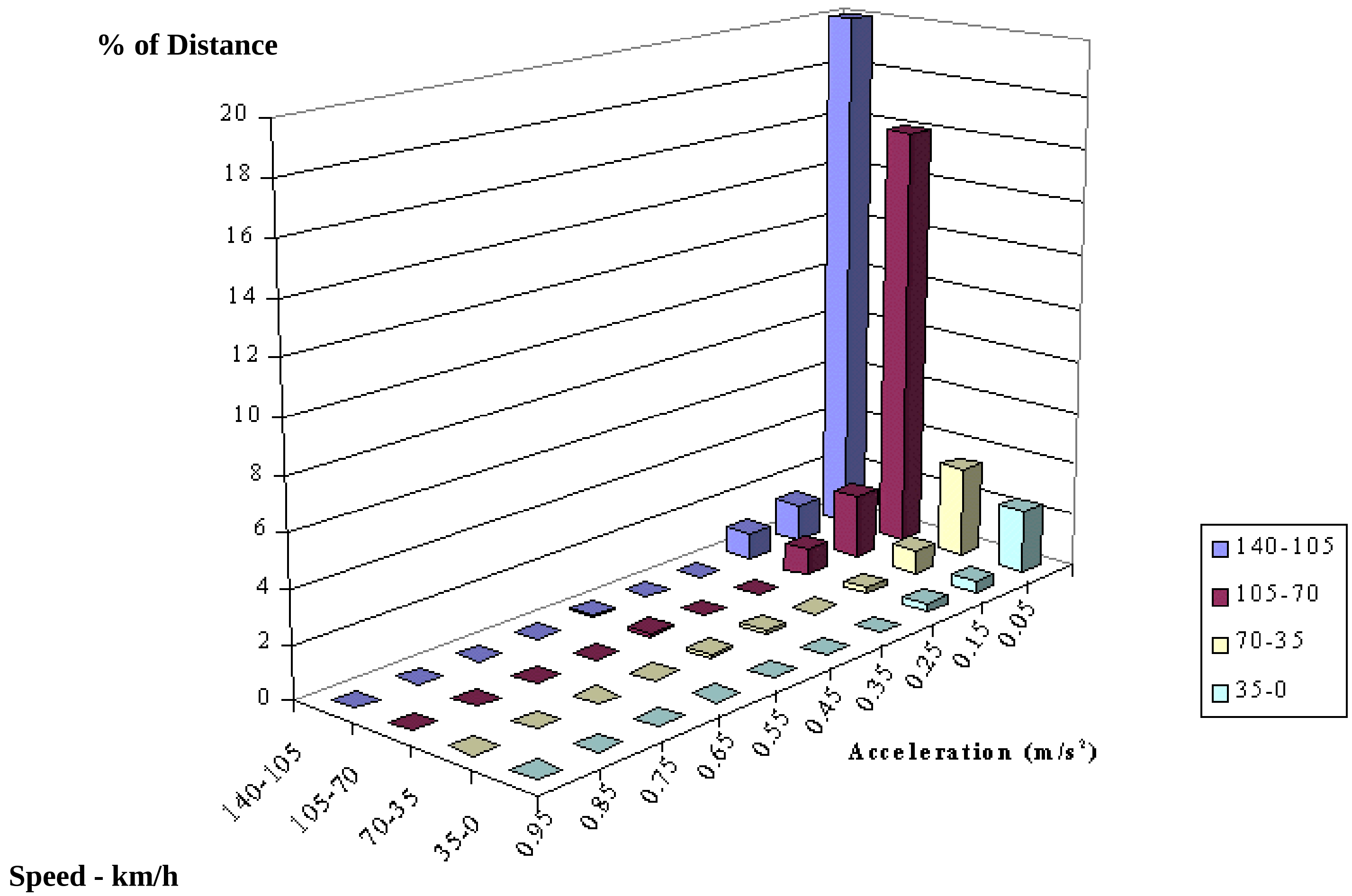


% of Distance
20
18
16
14
12
10
8
6
4
2
0
150-100
100-50
50-0
Speed - km/h
0.95
0.85
0.75
0.65
0.55
0.45
0.35
0.25
0.15
0.05
Acceleration (m/s²)
150-100
100-50
50-0

IN392


% of Time
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
140-105
105-70
70-35
35-0
Speed - km/h
0.95
0.85
0.75
0.65
0.55
0.45
0.35
0.25
0.15
0.05
Acceleration (m/s²)
140-105
105-70
70-35
35-0

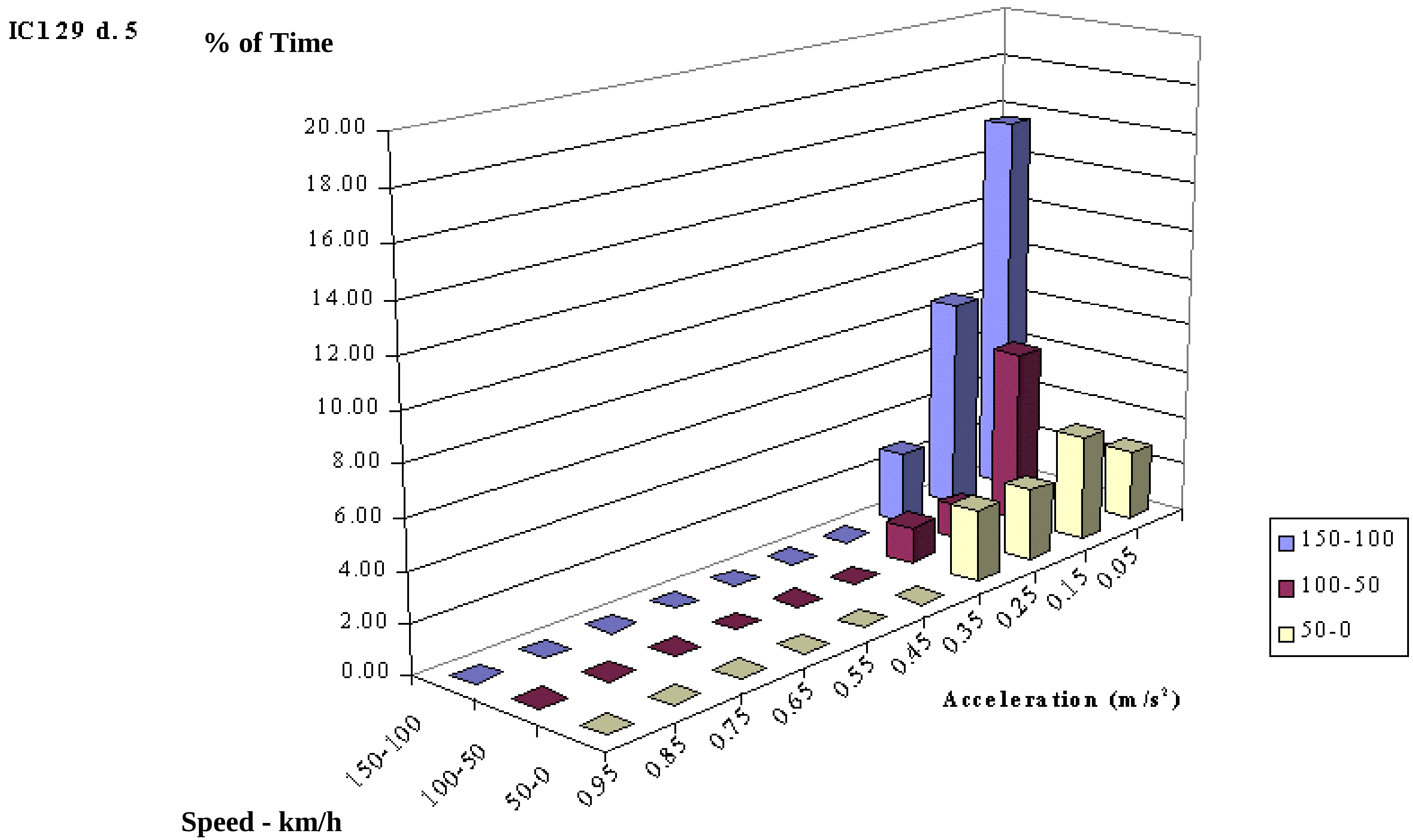
IN 3 9 2


% of Distance
20
18
16
14
12
10
8
6
4
2
0
Speed - km/h
140-105
105-70
70-35
35-0
Acceleration (m/s²)
0.95
0.85
0.75
0.65
0.55
0.45
0.35
0.25
0.15
0.05
140-105
105-70
70-35
35-0

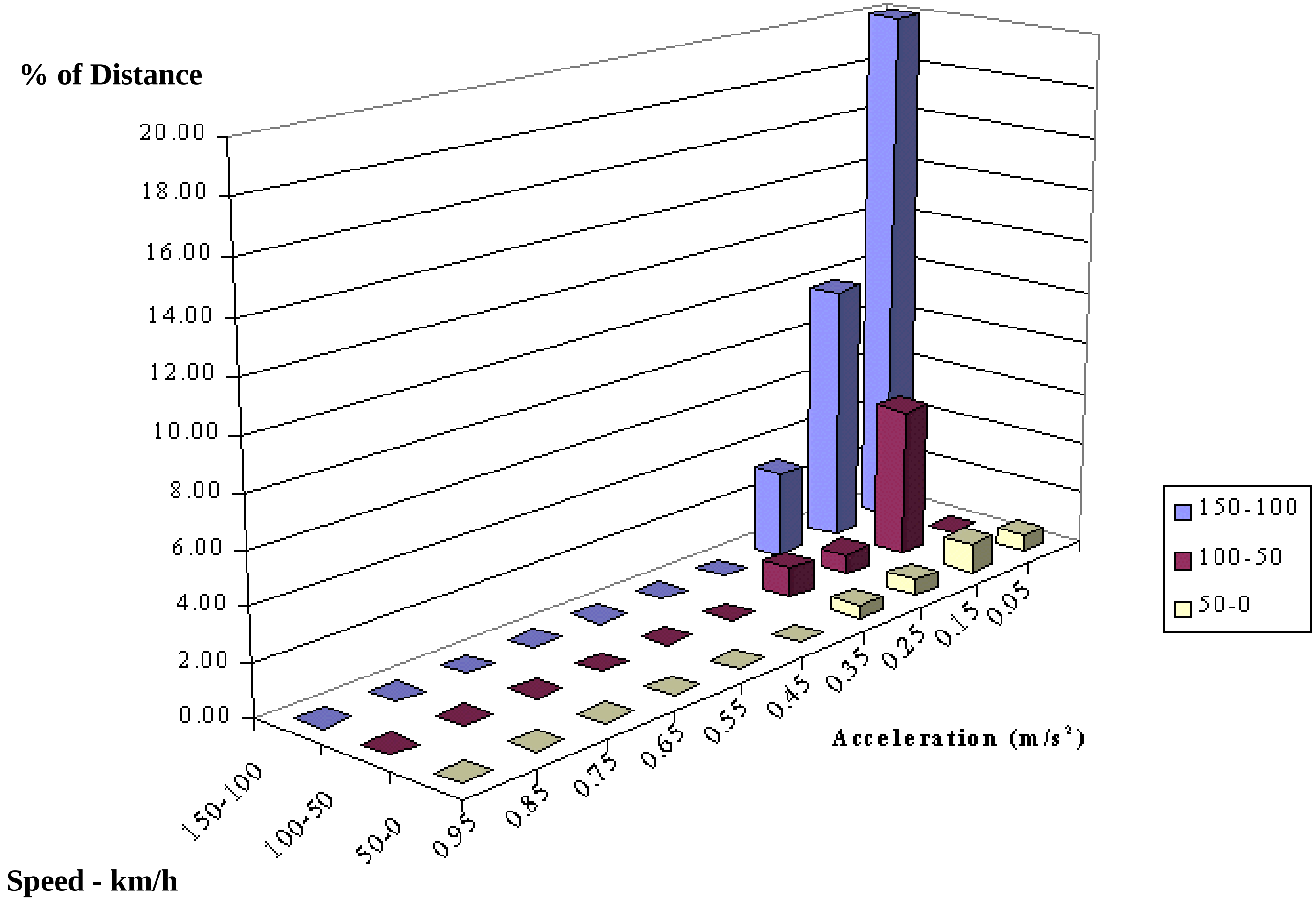
Appendix 13 Driving Distributions for IC129 d. 5 and d. 7

			Temporal Distribution				*Spatial Distribution*		
IC129 d. 5									
a_{MAX}	**a_{MIN}**		**Speed Interval**				**Speed Interval**		
			150-100	*100-50*	*50-0*		*150-100*	*100-50*	*50-0*
1	*0.9*		0.00	0.00	0.00		0.00	0.00	0.00
0.9	*0.8*		0.00	0.00	0.00		0.00	0.00	0.00
0.8	*0.7*		0.00	0.00	0.00		0.00	0.00	0.00
0.7	*0.6*		0.00	0.00	0.00		0.00	0.00	0.00
0.6	*0.5*		0.00	0.00	0.00		0.00	0.00	0.00
0.5	*0.4*		0.00	0.00	0.00		0.00	0.00	0.00
0.4	*0.3*		0.00	1.40	2.90		0.00	1.10	0.50
0.3	*0.2*		2.90	1.40	2.90		3.30	0.80	0.60
0.2	*0.1*		8.60	7.10	4.30		9.80	5.70	1.10
0.1	*0*		15.70	0.00	2.90		23.40	0.00	0.60

IC129 d. 7									
a_{MAX}	**a_{MIN}**		**Speed Interval**				**Speed Interval**		
			150-100	*100-50*	*50-0*		*150-100*	*100-50*	*50-0*
1	*0.9*		0.00	0.00	0.00		0.00	0.00	0.00
0.9	*0.8*		0.00	0.00	0.00		0.00	0.00	0.00
0.8	*0.7*		0.00	0.00	0.00		0.00	0.00	0.00
0.7	*0.6*		0.00	0.00	0.00		0.00	0.00	0.00
0.6	*0.5*		0.00	0.00	0.00		0.00	0.00	0.00
0.5	*0.4*		0.00	0.00	0.00		0.00	0.00	1.30
0.4	*0.3*		0.00	1.40	2.90		0.00	0.00	3.80
0.3	*0.2*		2.90	1.40	2.90		2.50	12.70	2.50
0.2	*0.1*		8.60	7.10	4.30		13.90	8.90	1.30
0.1	*0*		15.70	0.00	2.90		10.10	1.30	2.50


IC1 29 d. 5
% of Time
20.00
18.00
16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
150-100
100-50
50-0
0.95
0.85
0.75
0.65
0.55
0.45
0.35
0.25
0.15
0.05
Acceleration (m/s²)
Speed - km/h
150-100
100-50
50-0

IC129 d.5



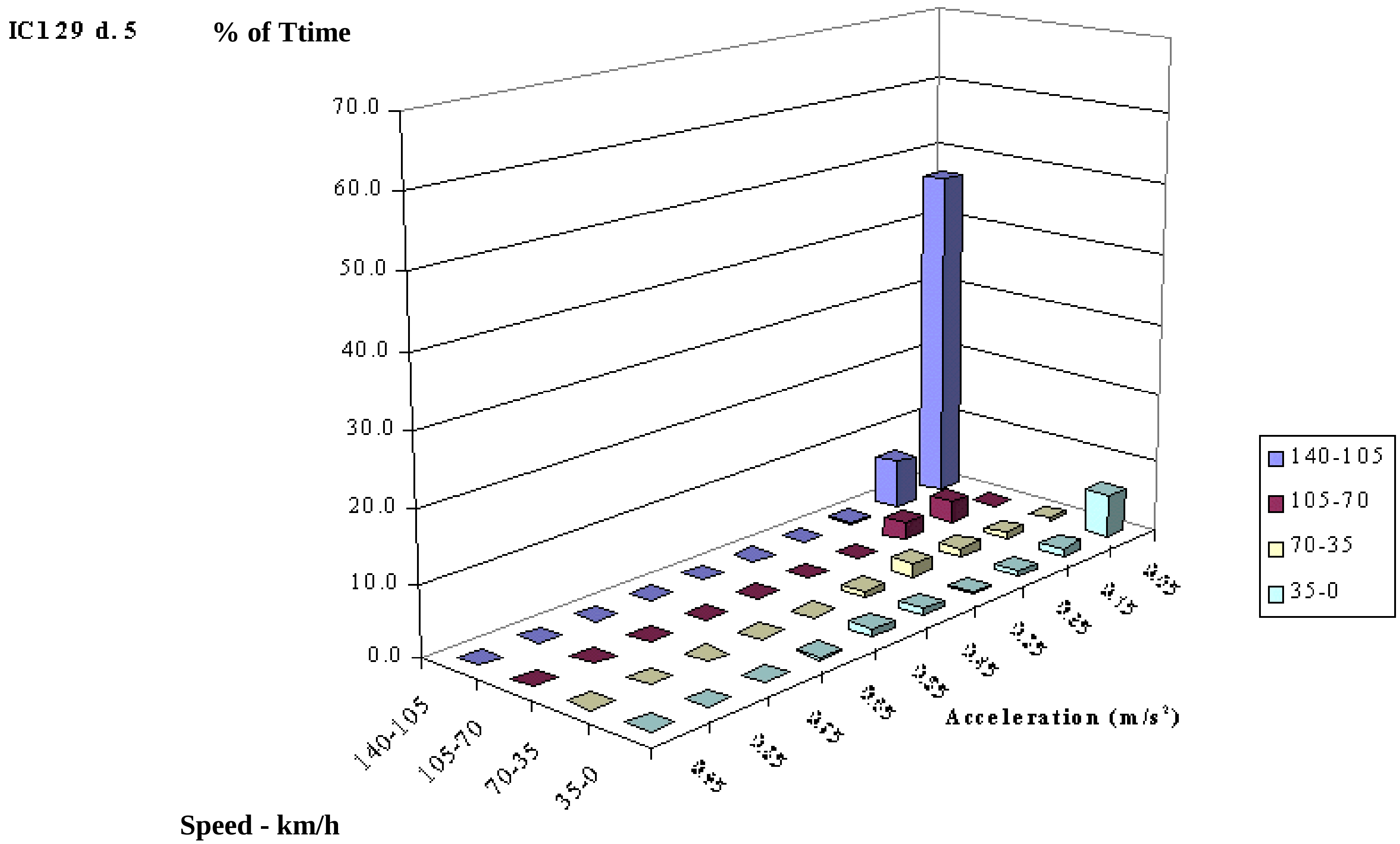
% of Distance
20.00
18.00
16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
150-100
100-50
50-0
Speed - km/h
0.95
0.85
0.75
0.65
0.55
0.45
0.35
0.25
0.15
0.05
Acceleration (m/s²)
150-100
100-50
50-0

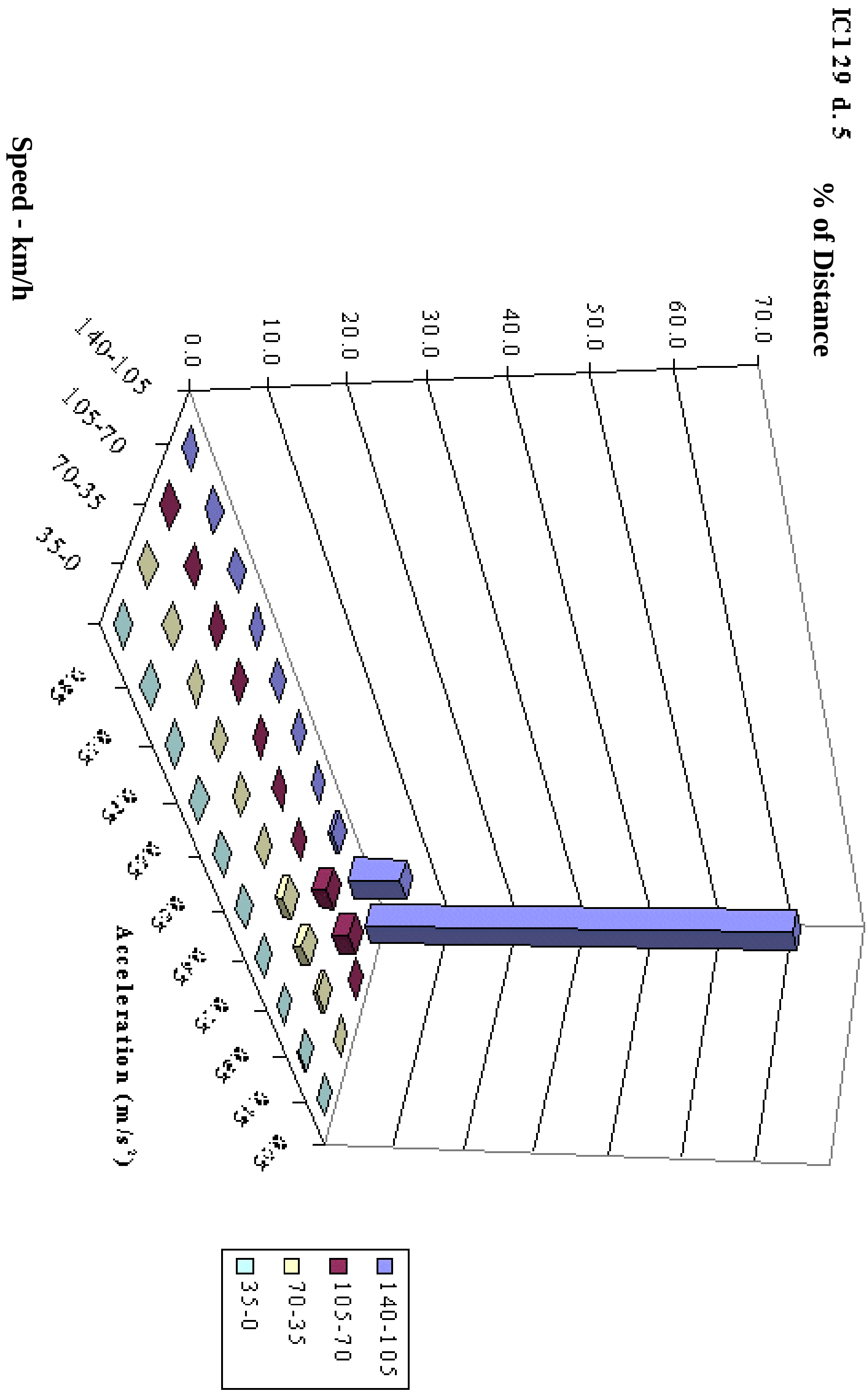
Appendix 14 Distributions for IC129 d. 5 and 8 and IC133 d. 8

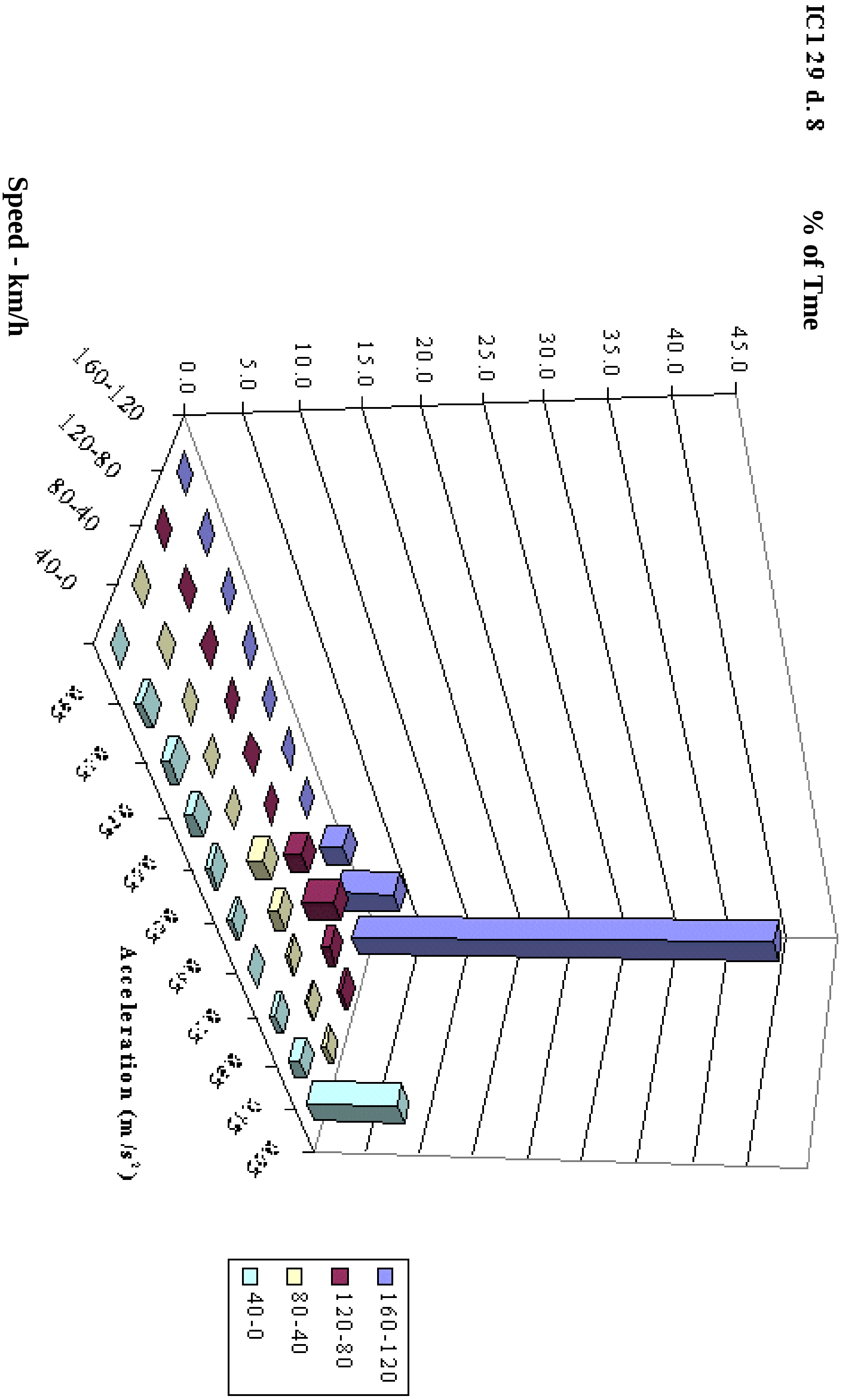
			Temporal Distribution					Spatial Distribution			
IC129 d. 5											
a_{MAX}	**a_{MIN}**		**Speed Interval**					**Speed Interval**			
			140-105	*105-70*	*70-35*	*35-0*		*140-105*	*105-70*	*70-35*	*35-0*
1	*0.9*		0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0
0.9	*0.8*		0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0
0.8	*0.7*		0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0
0.7	*0.6*		0.0	0.0	0.0	0.3		0.0	0.0	0.0	0.1
0.6	*0.5*		0.0	0.0	0.0	1.1		0.0	0.0	0.0	0.2
0.5	*0.4*		0.0	0.0	0.8	0.8		0.0	0.0	0.3	0.1
0.4	*0.3*		0.0	0.0	1.9	0.3		0.0	0.0	1.2	0.0
0.3	*0.2*		0.3	2.5	1.4	0.5		0.3	2.1	0.9	0.1
0.2	*0.1*		6.8	3.0	0.8	1.1		7.8	2.6	0.4	0.2
0.1	*0*		46.9	0.0	0.3	6.0		61.8	0.0	0.1	0.0

IC129 d. 8											
a_{MAX}	**a_{MIN}**		**Speed Interval**					**Speed Interval**			
			160-120	*120-80*	*80-40*	*40-0*		*160-120*	*120-80*	*80-40*	*40-0*
1	*0.9*		0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0
0.9	*0.8*		0.0	0.0	0.0	0.6		0.0	0.0	0.0	0.1
0.8	*0.7*		0.0	0.0	0.0	0.9		0.0	0.0	0.0	0.2
0.7	*0.6*		0.0	0.0	0.0	0.9		0.0	0.0	0.0	0.2
0.6	*0.5*		0.0	0.0	0.0	0.3		0.0	0.0	0.0	0.1
0.5	*0.4*		0.0	0.0	1.5	0.3		0.0	0.0	0.9	0.2
0.4	*0.3*		0.0	1.8	1.2	0.0		0.0	1.5	0.6	0.0
0.3	*0.2*		2.4	3.0	0.3	0.6		2.8	2.9	0.2	0.1
0.2	*0.1*		5.6	0.9	0.3	1.2		6.8	0.8	0.1	0.1
0.1	*0*		40.2	0.3	0.3	8.6		54.2	0.2	0.2	0.1

IC133 d. 8											
a_{MAX}	**a_{MIN}**		**Speed Interval**					**Speed Interval**			
			180-135	*135-90*	*90-45*	*45-0*		*140-105*	*105-70*	*70-35*	*35-0*
1	*0.9*		0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0
0.9	*0.8*		0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0
0.8	*0.7*		0.0	0.0	0.0	0.6		0.0	0.0	0.0	0.1
0.7	*0.6*		0.0	0.0	0.0	0.6		0.0	0.0	0.0	0.0
0.6	*0.5*		0.0	0.0	0.0	1.5		0.0	0.0	0.0	0.4
0.5	*0.4*		0.0	0.0	0.9	0.3		0.0	0.0	0.4	0.1
0.4	*0.3*		0.0	0.0	2.2	0.3		0.0	0.0	1.4	0.1
0.3	*0.2*		0.9	5.2	2.5	0.3		1.1	5.1	1.7	0.1
0.2	*0.1*		8.9	3.4	0.6	1.8		12.1	3.3	0.4	0.3
0.1	*0*		34.8	0.0	0.3	9.5		49.5	0.0	0.2	0.1

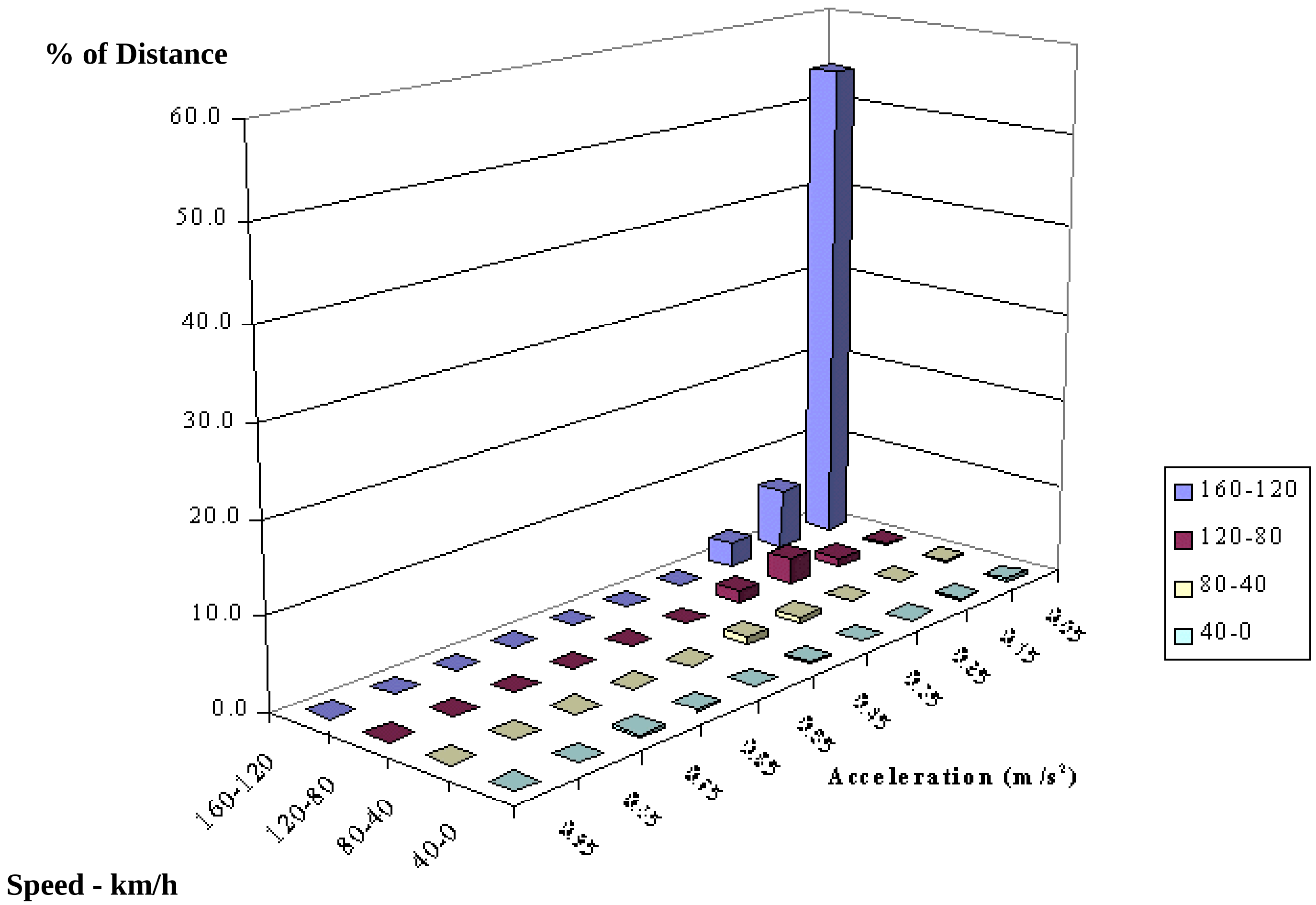

IC129 d.5
% of Ttime
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
140-105
105-70
70-35
35-0
Speed - km/h
Acceleration (m/s²)
140-105
105-70
70-35
35-0


IC129 d.5
% of Distance
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
Speed - km/h
140-105
105-70
70-35
35-0
Acceleration (m/s²)
140-105
105-70
70-35
35-0

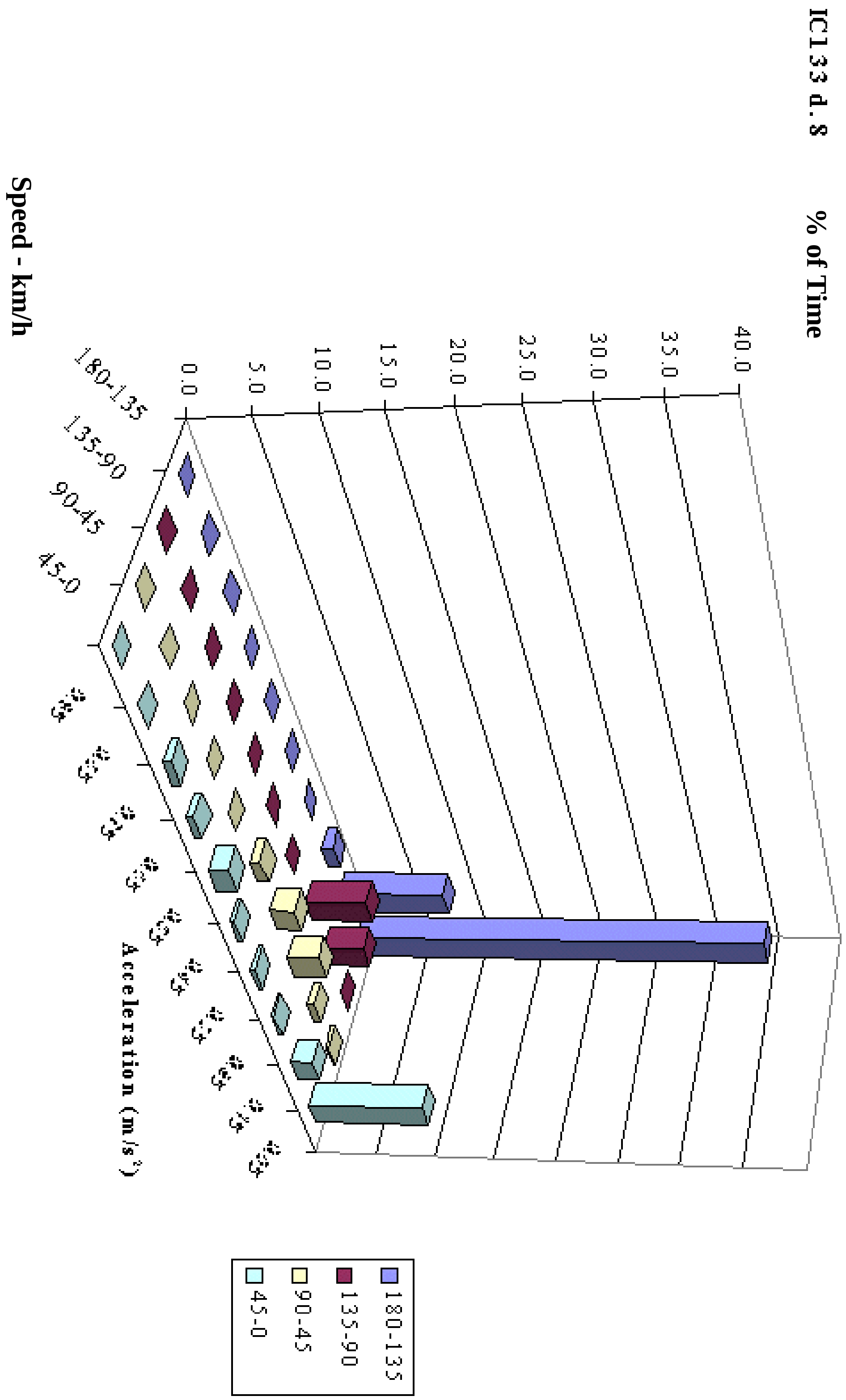


IC1 29 d. 8
% of Tme
45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
Speed - km/h
160-120
120-80
80-40
40-0
Acceleration (m/s²)
160-120
120-80
80-40
40-0

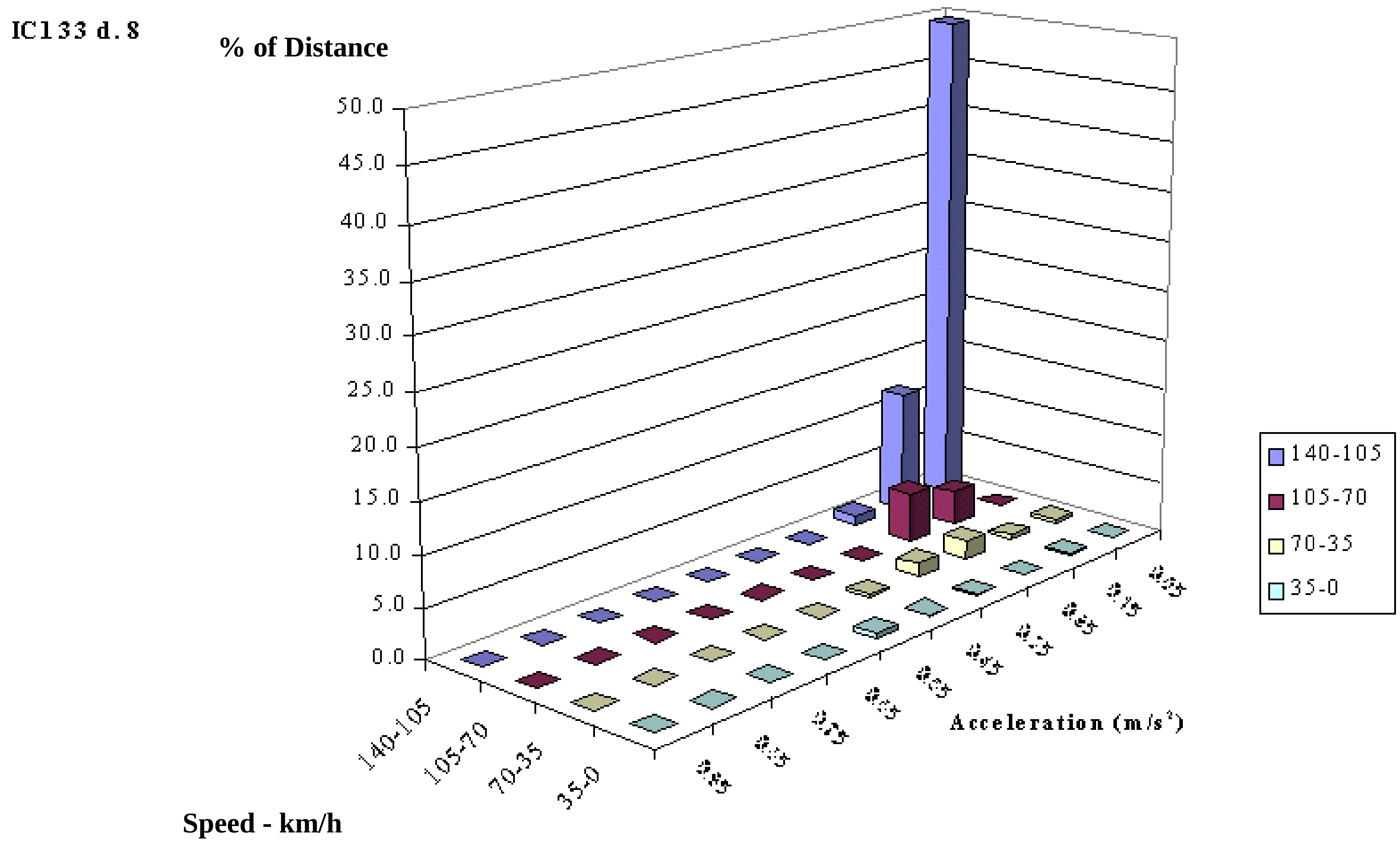
IC1 29 d. 8



% of Distance
60.0
50.0
40.0
30.0
20.0
10.0
0.0
160-120
120-80
80-40
40-0
Speed - km/h
Acceleration (m/s²)
160-120
120-80
80-40
40-0



IC133 d. 8
% of Time
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
Speed - km/h
180-135
135-90
90-45
45-0
Acceleration (m/s²)
180-135
135-90
90-45
45-0


IC133 d.8
% of Distance
50.0
45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
140-105
105-70
70-35
35-0
Speed - km/h
Acceleration (m/s²)
140-105
105-70
70-35
35-0

Appendix 15 Curves from the TRENDS project

Figure 6.3.3. Specific Energy Consumption of Diesel InterCity Trains

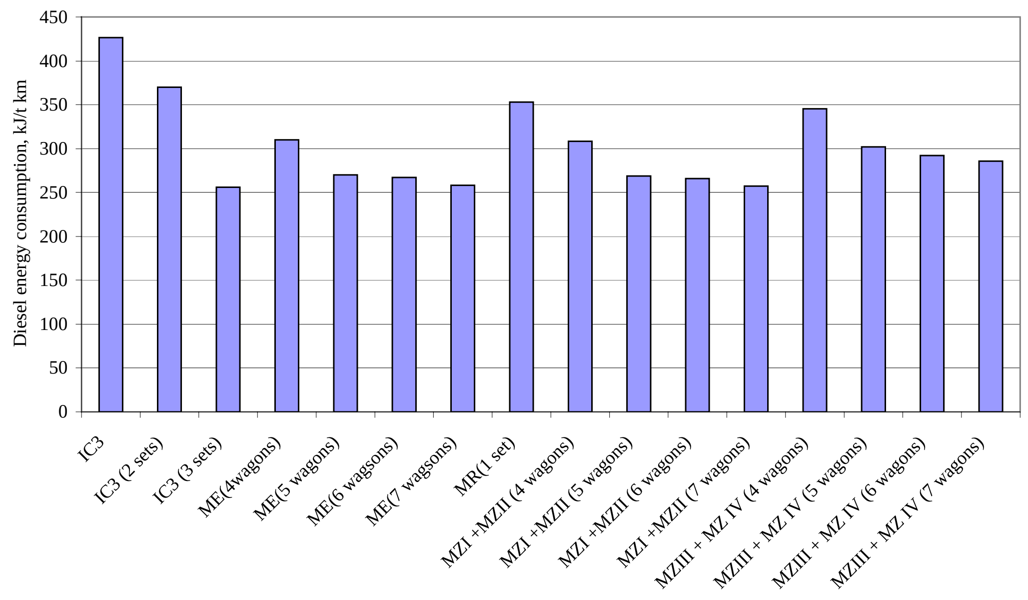


Figure 6.3.2. Electricity consumption of InterCity/Interregional Trains

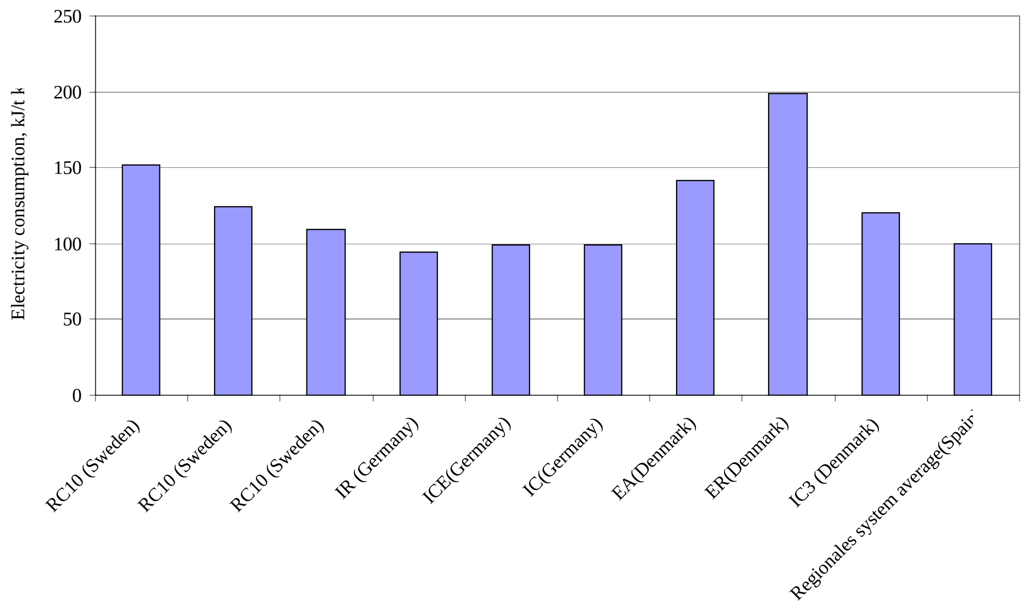


Figure 6.3.8. Tractive energy consumption of freight trains using combined diesel and electric train results

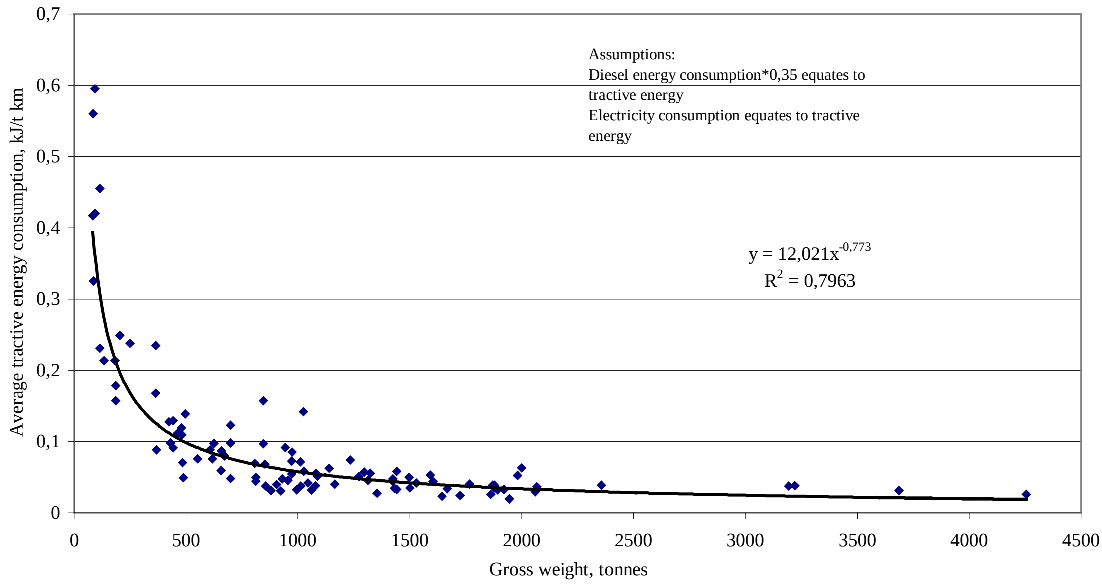
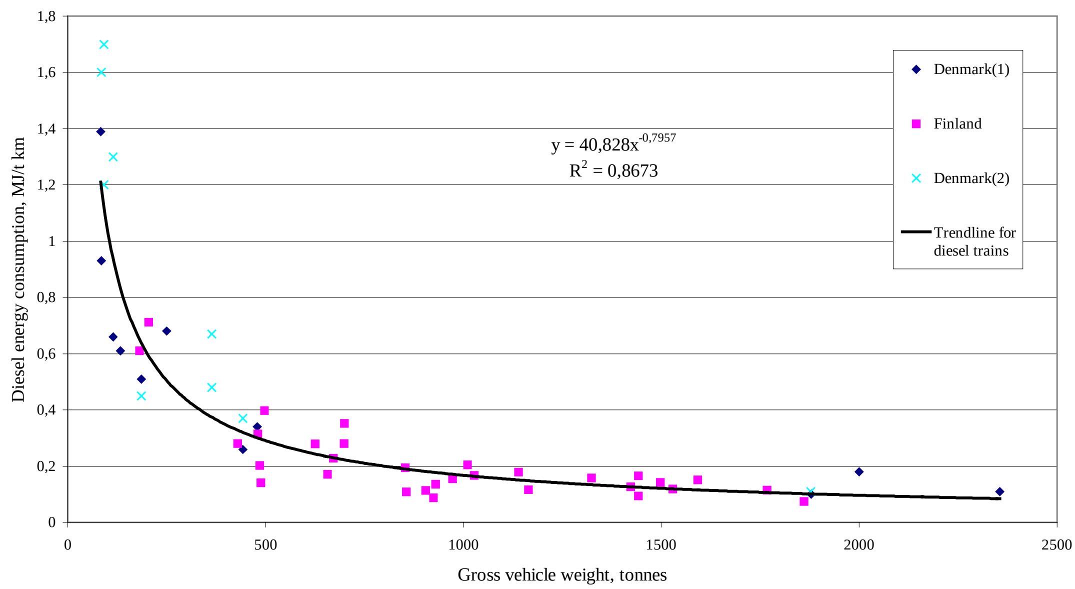
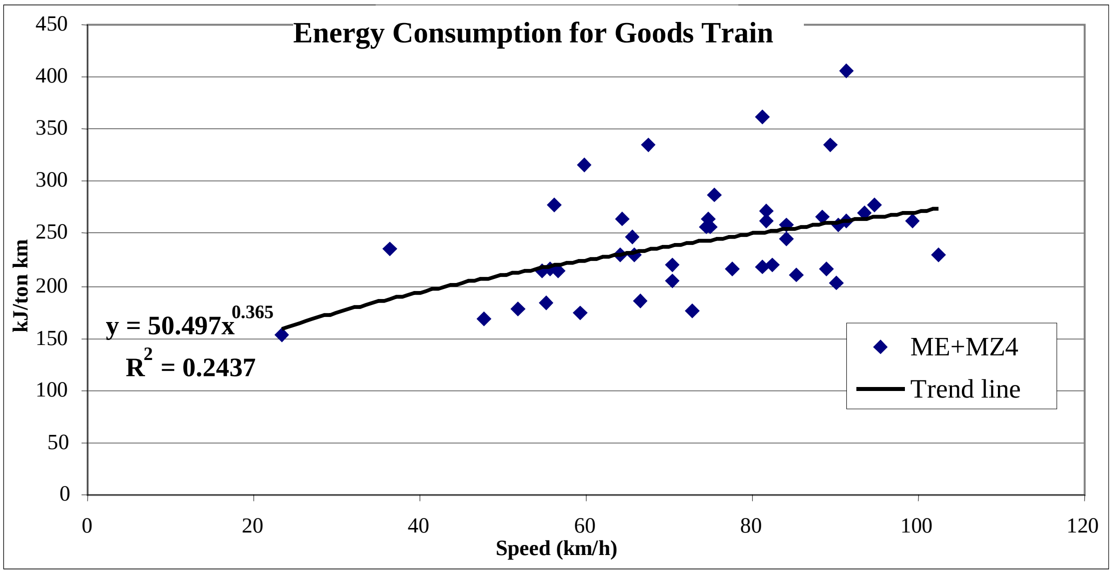


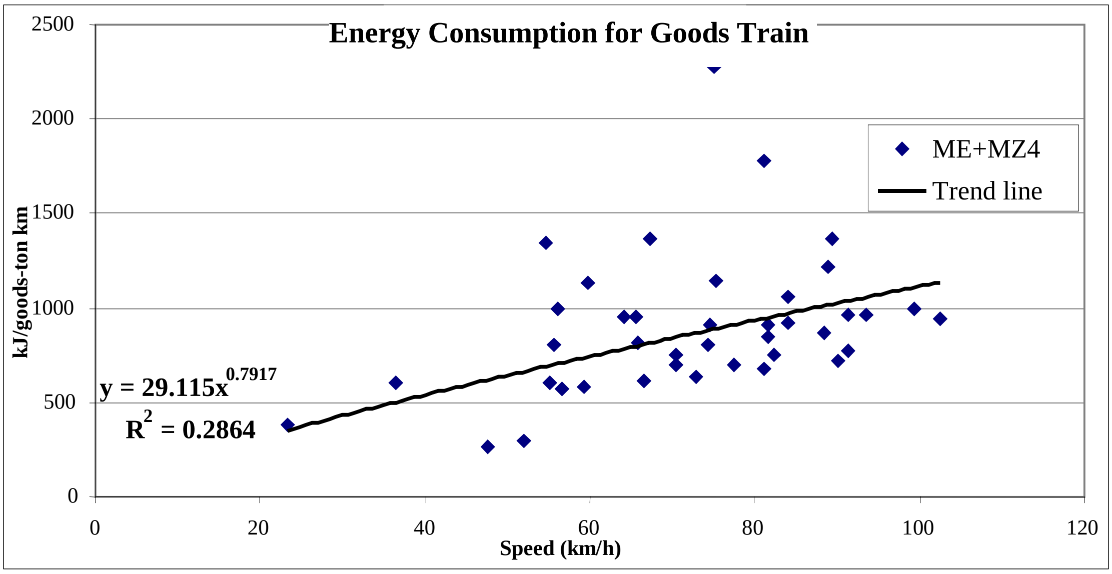
Figure 6.3.5 Diesel Energy Consumption of Diesel Freight Trains

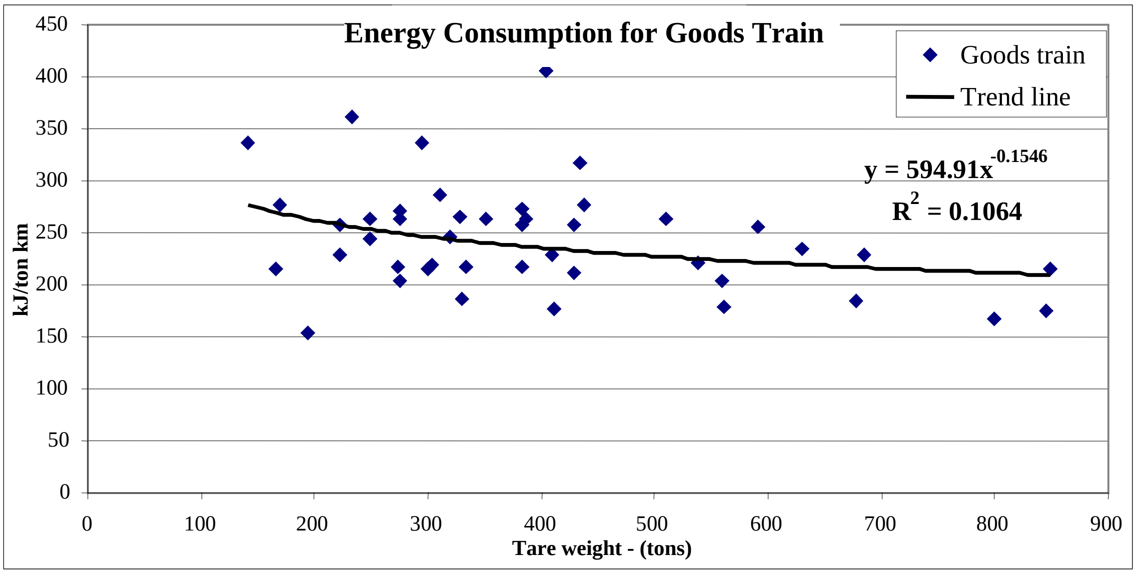


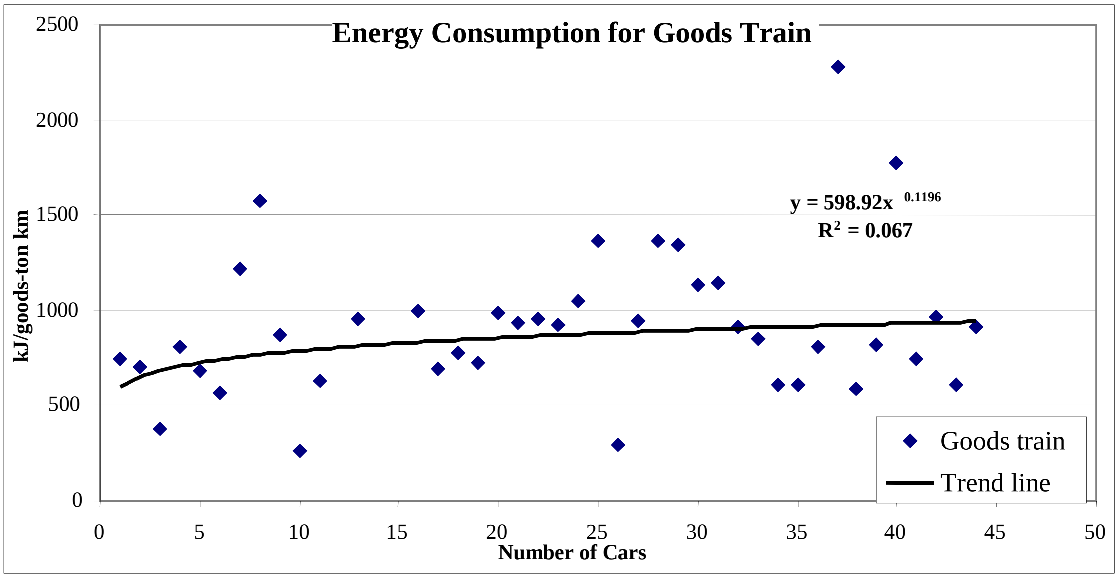
Appendix 16 Energy Consumption Tendencies

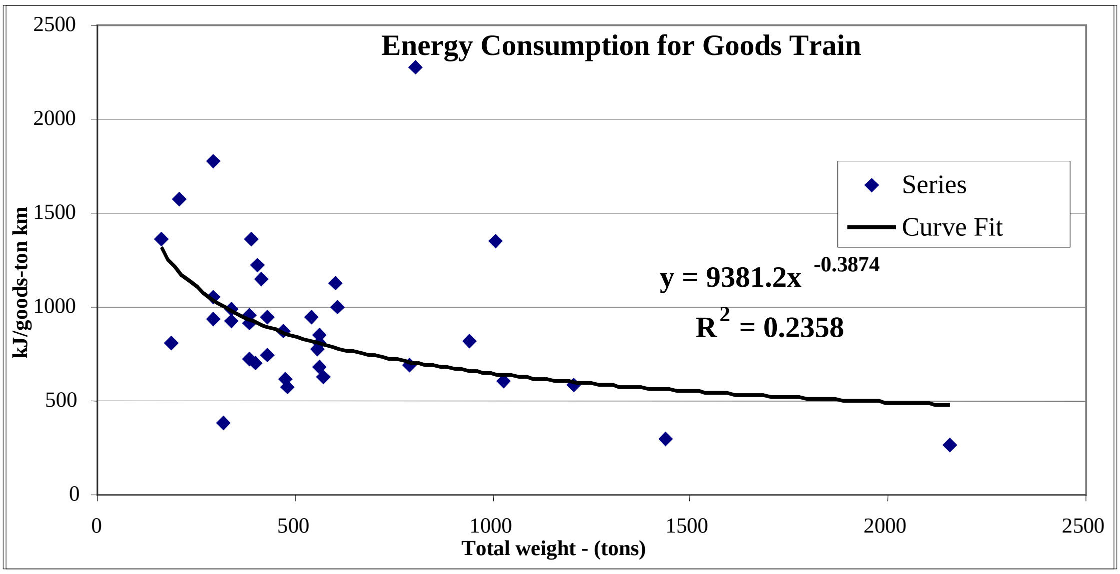
Goods train



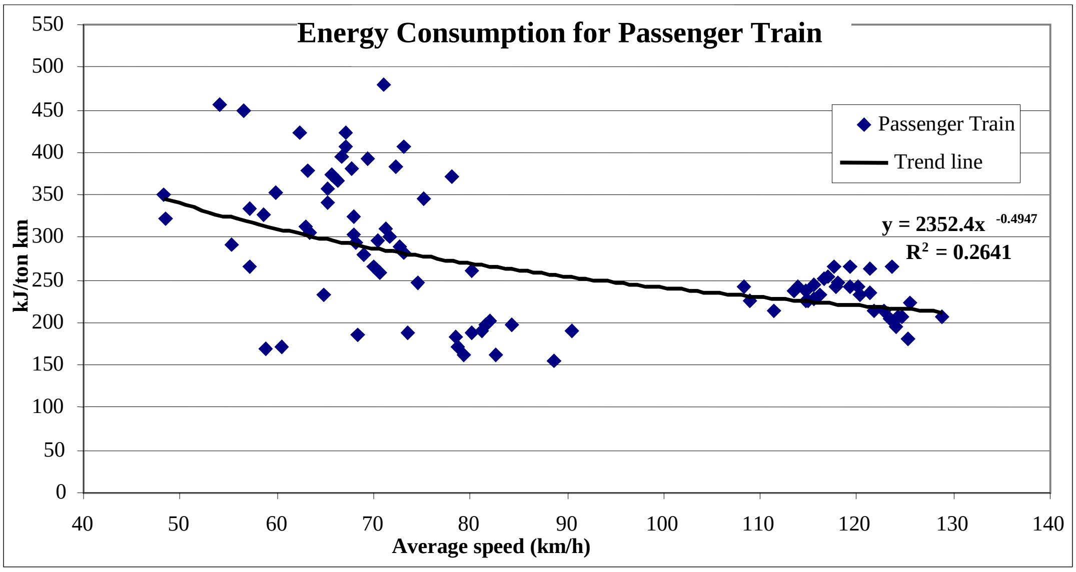


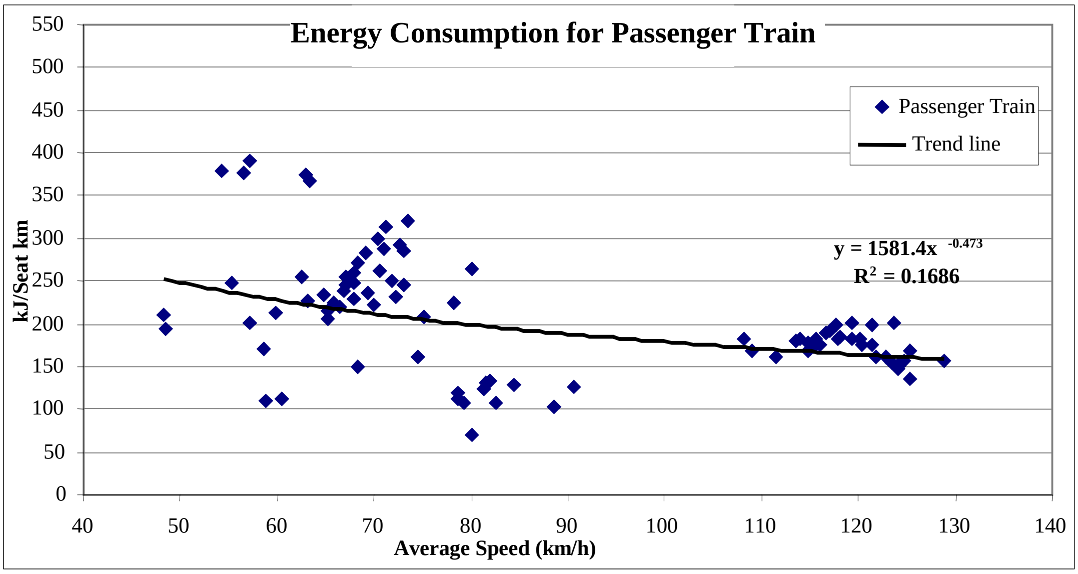

Energy Consumption for Goods Train
Goods train
Trend line
y = 594.91x^-0.1546
R^2 = 0.1064
kJ/ton km
0
50
100
150
200
250
300
350
400
450
0
100
200
300
400
500
600
700
800
900
Tare weight - (tons)

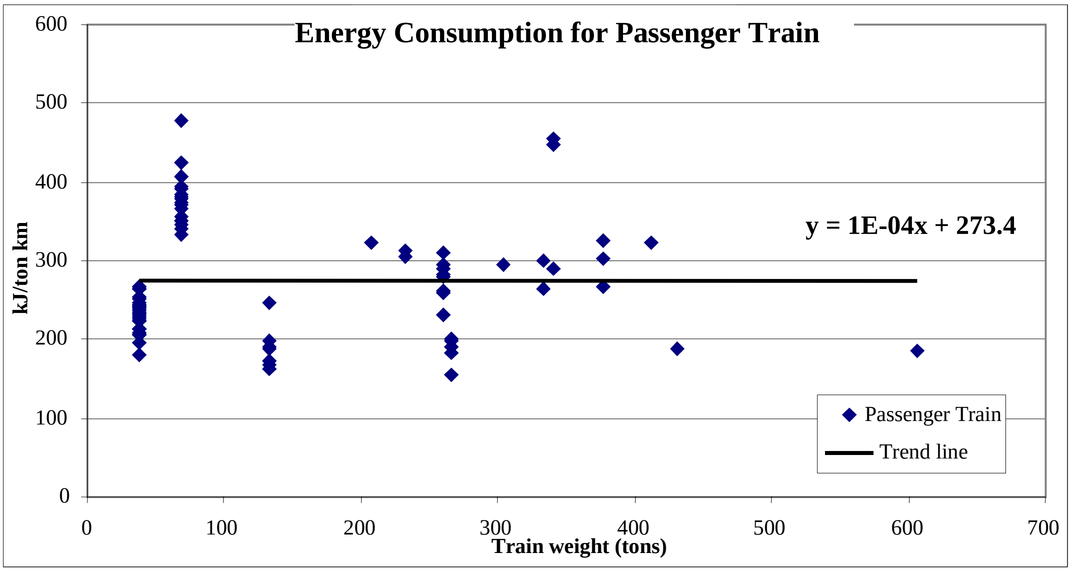

Energy Consumption for Goods Train
y = 598.92x 0.1196
R^2 = 0.067
Goods train
Trend line
kJ/goods-ton km
0
500
1000
1500
2000
2500
0
5
10
15
20
25
30
35
40
45
50
Number of Cars

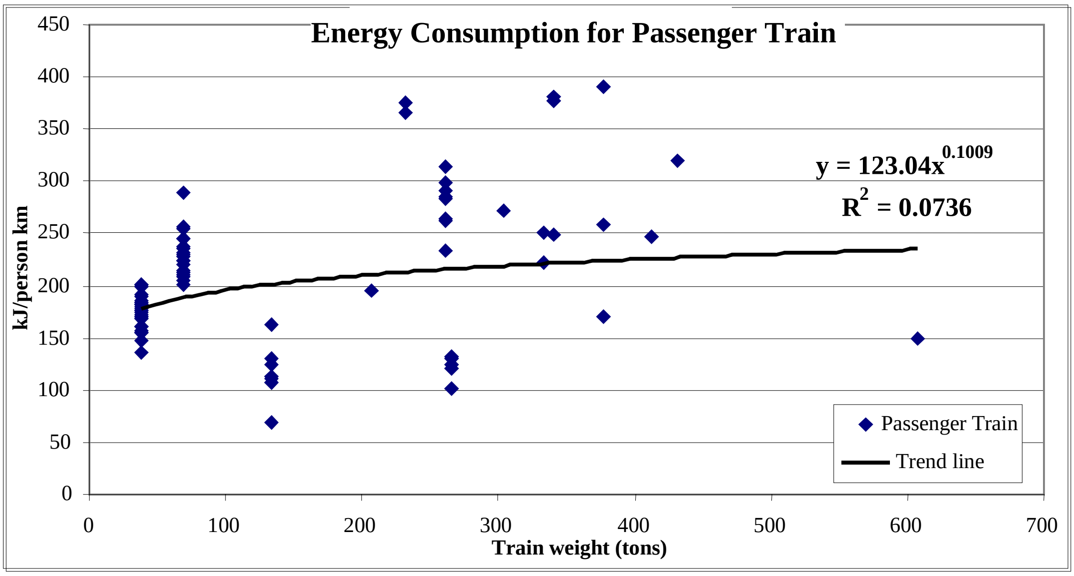

Energy Consumption for Goods Train
Series
Curve Fit
y = 9381.2x -0.3874
R^2 = 0.2358
kJ/goods-ton km
0
500
1000
1500
2000
2500
0
500
1000
1500
2000
2500
Total weight - (tons)

Passenger Train






Energy Consumption for Passenger Train
y = 1E-04x + 273.4
kJ/ton km
Train weight (tons)
Passenger Train
Trend line
0
100
200
300
400
500
600
700


Energy Consumption for Passenger Train
y = 123.04x^0.1009
R^2 = 0.0736
kJ/person km
Train weight (tons)
Passenger Train
Trend line
0
50
100
150
200
250
300
350
400
450
500
600
700

Appendix 17 Goods wagon specifications

Type	No. of axles	Tare wt. tons	Max capacity	Max weight	Length m	Tare wt. per axle	Load per axle	Max wt per axle	Weight per m
Closed Goods wagons									
Hbis	2	13.9	26.5	40.4	14.02	6.95	13.25	20.2	2.88
Hbillns	2	15.8	28.5	44.3	14.22	7.9	14.25	22.15	3.12
Hbbillns	2	16.3	28.5	44.8	15.5	8.15	14.25	22.4	2.89
Hbikks	2	15.5	24.5	40	14.02	7.75	12.25	20	2.85
Hios	2	14	26	40	10.58	7	13	20	3.78
Habbins	4	26.5	63.5	90	23.264	6.625	15.875	22.5	3.87
Habbillns	4	28.5	61.5	90	26.264	7.125	15.375	22.5	3.43
Habins-y	4	26.5	63.5	90	23.26	6.625	15.875	22.5	3.87
Habis 4	4	28	62	90	22.1	7	15.5	22.5	4.07
Hrrs	4	28	62	90	-	7	15.5	22.5	-
Open Goods wagons									
Eaos	4	21.8	58	79.8	14.04	5.45	14.5	19.95	5.68
Ks	2	12.5	27.5	40	13.86	6.25	13.75	20	2.89
Kbs	2	12.5	27.5	40	13.96	6.25	13.75	20	2.87
Lgjns	2	11.2	31.5	42.7	14.8	5.6	15.75	21.35	2.89
Rs	4	25.4	54.5	79.9	19.9	6.35	13.625	19.975	4.02
Sgmns	4	18.5	71.3	89.8	17.54	4.625	17.825	22.45	5.12
Sdgmns	4	20.4	62.5	82.9	18.34	5.1	15.625	20.725	4.52
Rilns	4								
Laaps	2								
Lps	2	45	28	73	14.02	22.5	14	36.5	5.21
Rns-u	4	24	66	90	19.9	6	16.5	22.5	4.52
Laas	4	26	54	80	27	6.5	13.5	20	2.96
Laaimms	4	27	63	90	-	6.75	15.75	22.5	-
Res	4	25	55	80	19.9	6.25	13.75	20	4.02
Container wagons									
Tdgs	2	12.8	27.5	40.3	9.64	6.4	13.75	20.15	4.18
Ucs	2	11	29	40	9.64	5.5	14.5	20	4.15
Zagkks	4	-	-	-	-	-	-	-	-
Zaes	4	-	-	-	-	-	-	-	-
Zcs	2	-	-	-	-	-	-	-	-
Zs	2	-	-	-	-	-	-	-	-
Zckk	2	-	-	-	-	-	-	-	-
Laados	2	-	-	-	-	-	-	-	-
Special wagons									
Sins	4	28	62		-	-	-	-	-
Shimmns	4	22.6	67		-	-	-	-	-
Snps	4	26.5	61.5		20.84	6.625	15.375	22	4.22
Ave. values	**3.09**	**21.60**	**47.86**	**67.00**	**17.24**	**7.13**	**14.68**	**21.81**	**3.83**

Appendix 18 Goods Trains sizes and weights

Date	Loco-motive	Train cat.	Train no	From st	To st	Shipping weight	Total Weight tons	Total no. wagons
9/15/99	ME	GS	7495	FA	ÅR	144.00	415.56	18
9/15/99	ME	GS	7495	GB	RG	168.00	486.44	21
9/15/99	ME	GS	7495	RG	FA	224.00	646.38	28
9/20/99	ME	GS	7495	FA	ÅR	152.00	443.75	19
9/20/99	ME	GS	7495	GB	RG	168.00	491.69	21
9/20/99	ME	GS	7495	RG	FA	232.00	676.94	29
9/24/99	ME	GS	7495	FA	ÅR	152.00	441.38	19
9/24/99	ME	GS	7495	GB	RG	168.00	491.06	21
9/24/99	ME	GS	7495	RG	FA	232.00	676.38	29
9/28/99	ME	GS	7495	FA	ÅR	152.00	440.25	19
9/28/99	ME	GS	7495	GB	RG	168.00	481.75	21
9/28/99	ME	GS	7495	RG	FA	232.00	668.38	29
10/13/99	ME	GS	7495	FA	ÅR	160.00	459.47	20
10/13/99	ME	GS	7495	GB	RG	168.00	488.75	21
10/13/99	ME	GS	7495	RG	FA	240.00	694.44	30
12/9/99	ME	GS	7495	FA	ÅR	160.00	465.44	20
12/9/99	ME	GS	7495	GB	RG	168.00	487.25	21
12/9/99	ME	GS	7495	RG	FA	240.00	698.75	30
7/28/99	ME	GS	7499	FA	ÅR	104.00	301.38	13
7/28/99	ME	GS	7499	GB	RG	264.00	764.94	33
7/28/99	ME	GS	7499	RG	FA	200.00	580.75	25
8/26/99	ME	GS	7499	FA	ÅR	96.00	302.00	12
8/26/99	ME	GS	7499	GB	RG	248.00	780.88	31
8/26/99	ME	GS	7499	RG	FA	184.00	559.88	23
9/27/99	ME	GS	7499	FA	ÅR	104.00	303.50	13
9/27/99	ME	GS	7499	GB	RG	272.00	794.75	34
9/27/99	ME	GS	7499	RG	FA	192.00	561.06	24
10/7/99	ME	GS	7499	FA	ÅR	104.00	300.19	13
10/7/99	ME	GS	7499	GB	RG	296.00	858.88	37
10/7/99	ME	GS	7499	RG	FA	208.00	602.88	26
1/25/99	ME	GP	7501	AR	TOV	90.00	223.97	5
1/25/99	ME	GP	7501	GL	OD	126.00	313.59	7
1/25/99	ME	GP	7501	HC	AR	144.00	358.38	8
1/25/99	ME	GP	7501	OD	HC	144.00	358.38	8
7/30/99	ME	GP	7501	AR	TOV	90.00	223.98	5
7/30/99	ME	GP	7501	GL	OD	126.00	313.58	7
7/30/99	ME	GP	7501	OD	AR	144.00	358.38	8
8/27/99	ME	GP	7502	FA	OD	162.00	429.98	10
8/27/99	ME	GP	7502	OD	RG	162.00	429.98	10
8/27/99	ME	GP	7502	RG	GL	126.00	340.39	8
8/27/99	ME	GP	7502	TOV	FA	90.00	250.78	6
10/5/99	ME	GP	7502	FA	RG	180.00	447.94	10
10/5/99	ME	GP	7502	RG	GL	144.00	358.38	8
10/5/99	ME	GP	7502	TOV	FA	108.00	268.78	6
10/8/99	ME	GP	7502	FA	RG	162.00	429.98	10
10/8/99	ME	GP	7502	RG	GL	126.00	340.39	8
10/8/99	ME	GP	7502	TOV	FA	90.00	250.77	6

9/15/99	ME	GP	7504	AR	FA	108.00	268.77	6
9/15/99	ME	GP	7504	FA	RG	90.00	223.97	5
9/15/99	ME	GP	7504	RG	GL	72.00	179.19	4
9/20/99	ME	GP	7504	AR	FA	108.00	268.77	6
9/20/99	ME	GP	7504	FA	RG	90.00	223.97	5
9/20/99	ME	GP	7504	RG	GL	72.00	179.19	4
9/24/99	ME	GP	7504	AR	FA	108.00	268.77	6
9/24/99	ME	GP	7504	FA	RG	90.00	223.97	5
9/24/99	ME	GP	7504	RG	GL	72.00	179.19	4
9/28/99	ME	GP	7504	AR	FA	108.00	268.77	6
9/28/99	ME	GP	7504	FA	RG	90.00	223.97	5
9/28/99	ME	GP	7504	RG	GL	72.00	179.19	4
10/13/99	ME	GP	7504	AR	FA	108.00	268.77	6
10/13/99	ME	GP	7504	FA	RG	90.00	223.97	5
10/13/99	ME	GP	7504	RG	GL	72.00	179.19	4
12/9/99	ME	GP	7504	AR	FA	108.00	268.77	6
12/9/99	ME	GP	7504	FA	RG	90.00	223.97	5
12/9/99	ME	GP	7504	RG	GL	72.00	179.19	4
8/2/99	ME	GP	7515	AR	AB	18.00	44.80	1
9/3/99	ME	GP	7516	FA	GL	108.00	268.78	6
9/3/99	ME	GP	7516	TOV	FA	36.00	89.59	2
9/6/99	ME	GP	7516	FA	GL	180.00	447.97	10
9/6/99	ME	GP	7516	TOV	FA	36.00	89.59	2
9/20/99	ME	GP	7516	FA	GL	180.00	447.97	10
9/20/99	ME	GP	7516	TOV	FA	36.00	89.59	2
9/3/99	ME	GP	7523	AR	TOV	54.00	134.39	3
9/3/99	ME	GP	7523	FA	AR	108.00	268.78	6
9/3/99	ME	GP	7523	GL	FA	126.00	313.59	7
9/3/99	ME	G	7915	ÅR	AB	172.00	484.44	21
9/2/99	ME	GP	8603	AR	TOV	80.00	213.97	5
9/2/99	ME	GP	8603	GL	AR	142.00	383.19	9
8/2/99	ME	GS	9120	OD	RG	152.00	440.69	19
8/2/99	ME	GS	9120	RG	GB	96.00	278.78	12
8/2/99	ME	GS	9120	ÅR	OD	168.00	533.59	24
8/25/99	ME	GP	9134	GL	GB	54.00	134.39	3
8/25/99	ME	GP	9134	RG	GL	18.00	125.19	4
9/14/99	ME	GP	9134	GL	GB	44.00	124.39	3
9/14/99	ME	GP	9134	RG	GL	8.00	115.19	4
10/25/99	MZ	GP	9134	GL	GB	44.00	129.79	4
10/25/99	MZ	GP	9134	RG	GL	8.00	120.58	5
9/13/99	ME	G	9217	GB	HTÅ	399.10	914.43	25
9/13/99	ME	G	9217	HTÅ	RG	249.00	550.46	15
9/13/99	ME	G	9217	NÆ	NF	21.00	71.79	3
9/13/99	ME	G	9217	RG	NÆ	215.40	691.85	29
9/20/99	ME	G	9217	GB	HTÅ	357.60	1087.24	39
9/20/99	ME	G	9217	HTÅ	RG	254.80	824.07	32
9/20/99	ME	G	9217	NÆ	NF	59.50	177.39	7
9/20/99	ME	G	9217	RG	NÆ	248.30	771.67	29
7/28/99	ME	G	9219	GB	HTÅ	107.20	214.59	5
7/28/99	ME	G	9219	HTÅ	RG	107.20	214.59	5

7/28/99	ME	G	9219	NÆ	NF	20.00	36.30	1
7/28/99	ME	G	9219	RG	NÆ	96.40	178.29	4
9/8/99	ME	G	9219	GB	RG	327.40	680.44	16
9/8/99	ME	G	9219	NÆ	NF	27.00	43.50	1
9/8/99	ME	G	9219	RG	NÆ	312.60	610.76	13
9/16/99	ME	G	9219	GB	RG	82.30	395.58	20
9/16/99	ME	G	9219	NÆ	NF	55.00	87.50	2
9/16/99	ME	G	9219	RG	NÆ	129.30	448.28	21
10/20/99	ME	G	9219	GB	RG	82.30	438.67	23
10/20/99	ME	G	9219	NÆ	NF	55.00	106.20	3
10/20/99	ME	G	9219	RG	NÆ	78.70	393.27	21
10/30/99	MZ	G	9221	GB	NÆ	169.80	362.09	8
10/30/99	MZ	G	9254	NÆ	GB	380.00	585.47	15
9/15/99	MZ	G	9282	HTÅ	GB	224.40	543.27	17
9/15/99	MZ	G	9282	NF	RG	4.00	22.30	1
9/15/99	MZ	G	9282	RG	HTÅ	224.40	543.27	17
10/21/99	MZ	G	9282	HTÅ	GB	164.90	594.86	24
10/21/99	MZ	G	9282	NF	RG	132.90	262.28	7
10/21/99	MZ	G	9282	RG	HTÅ	164.90	594.86	24
10/25/99	MZ	G	9282	HTÅ	GB	90.20	660.27	29
10/25/99	MZ	G	9282	NF	RG	48.20	97.29	3
10/25/99	MZ	G	9282	RG	HTÅ	90.20	660.27	29
9/27/99	MZMZ	G	9409	GB	KJ	1681.20	2471.41	40
2/25/99	MZ	G	9425	GB	KJ	878.00	1316.36	36
1/27/99	ME	G	89106	OD	RG	112.00	315.59	14
1/27/99	ME	G	89106	RG	GB	96.00	274.88	12
8/23/99	MZ	G	89448	GL	GB	268.00	497.38	14
8/23/99	MZ	G	89448	KJ	GL	268.00	497.38	14

Source: DSB

Appendix 19 Goods Transport from Denmark

(source: Banestyrelsen)

1997 divided into 3 periods:

	Start	End	#days	Note:
Period 1:	01.01.97	05.04.97	95,00	Storebælt connection not open
Period 2:	06.04.97	31.05.97	56,00	Storebælt connection only open for goods trains
Period 3:	01.06.97	31.12.97	213,00	Storebælt connection open for both passenger and goods trains
			364,00	

Goods traffic 1997, Period 1

Diesel/electric	Gross ton-km	Goods ton-km	Train km	Goods wt./train	Goods wt./wagon
Diesel	979.830.263	434.699.609	1.637.100	223	13,8
Electric	5.176.537	2.161.815	7.941	259	11,6
Total	985.006.800	436.861.424	1.645.041	223	13,8

Goods traffic 1997, Period 2

Diesel/electric	Gross ton-km	Goods ton-km	Train km	Goods wt./train	Goods wt./wagon
Diesel	466.419.409	208.970.367	687.727	247	14,8
Electric	216.226.047	94.952.147	270.569	349	15,5
Total	682.645.456	303.922.514	958.296	267	14,9

Goods traffic 1997, Periode3

Diesel/electric	Gross ton-km	Goods ton-km	Train km	Goods wt./train	Goods wt./wagon
Diesel	1.226.141.969	512.452.151	2.401.863	209	41,5
Electric	1.685.526.766	808.869.424	1.915.835	407	20,1
Total	2.911.668.735	1.321.321.575	4.317.698	268	16,2

1997, Periode 1

Diesel/el	Gross ton-km	Goods ton-km	Train km
Diesel	99%	100%	100%
Electric	1%	0%	0%
Total	100%	100%	100%

1997, Periode 2

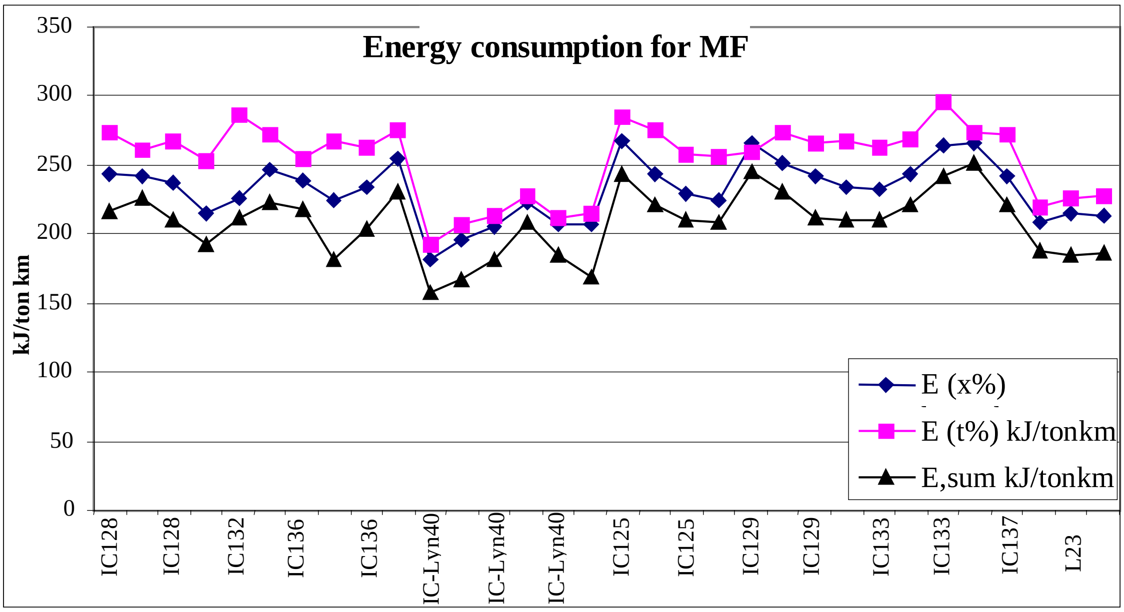
Diesel/el	Gross ton-km	Goods ton-km	Train km
Diesel	69%	69%	72%
Electric	32%	31%	28%
Total	100%	100%	100%

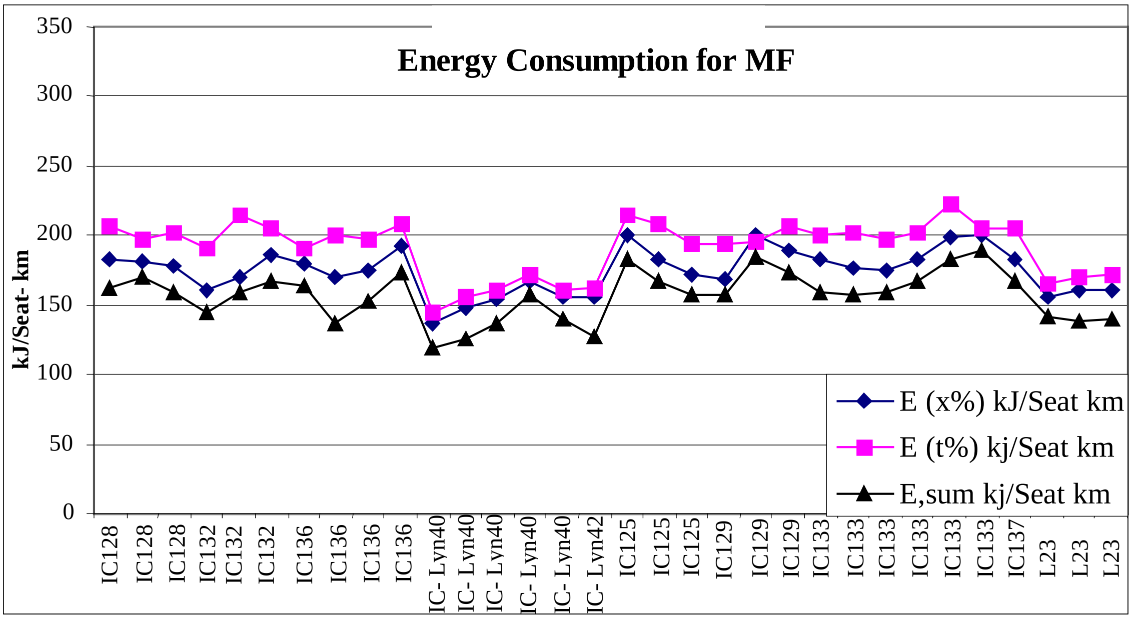
1997, Periode 3

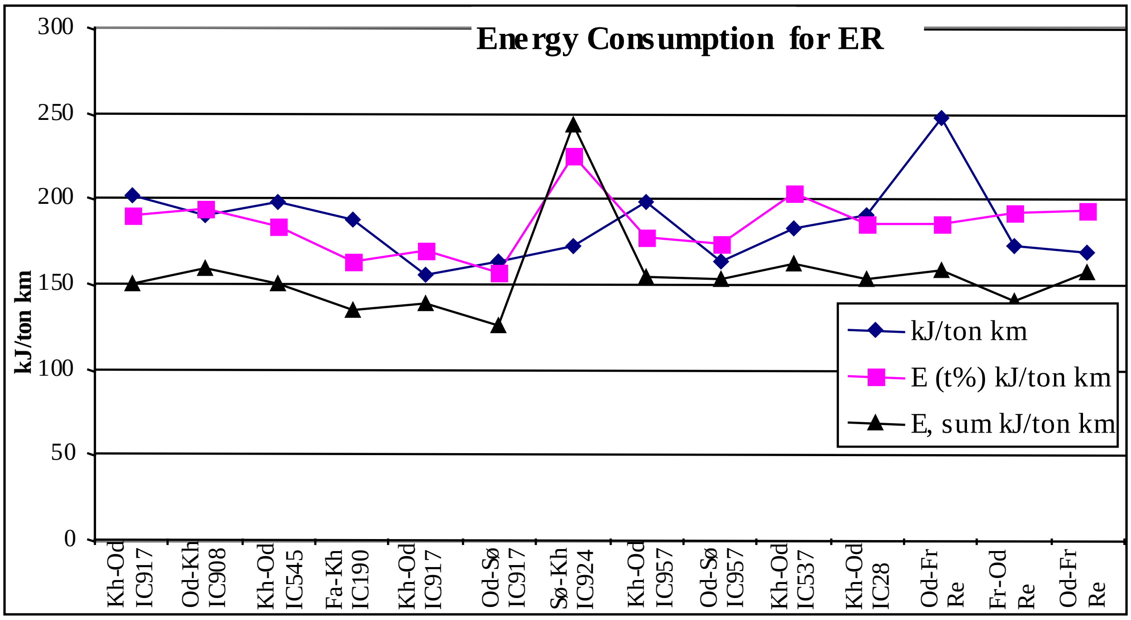
Diesel/el	Bruttotonkm	Godstonkm	Togkm
Diesel	42%	39%	56%
El	58%	61%	44%
Ialt	100%	100%	100%

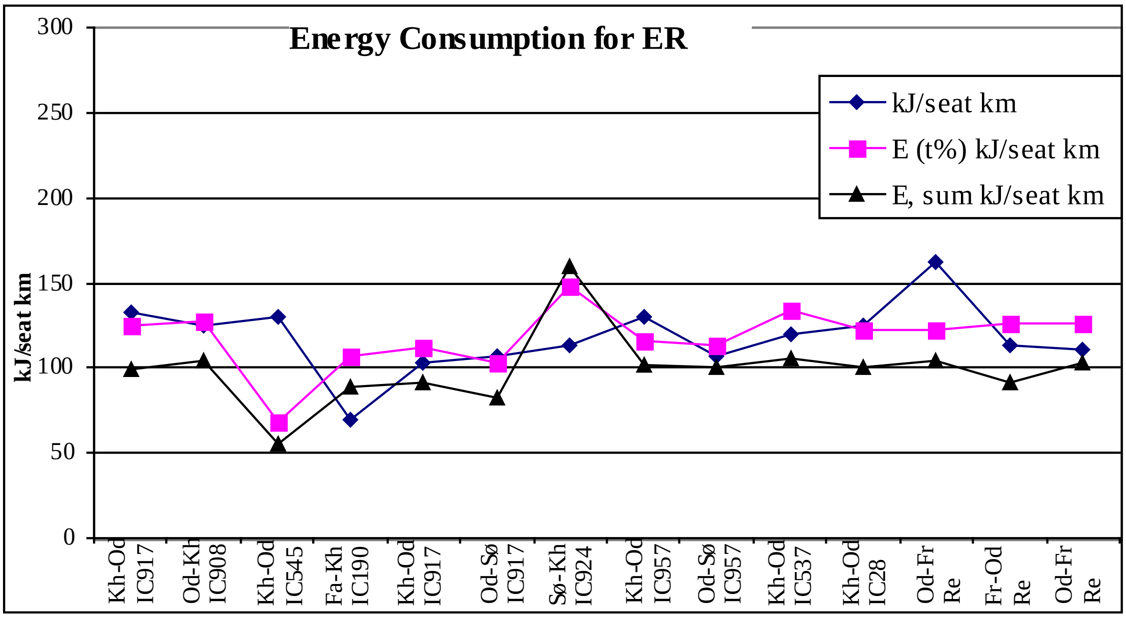
Note: Average goods weight per wagon is weighted by the number of trains.

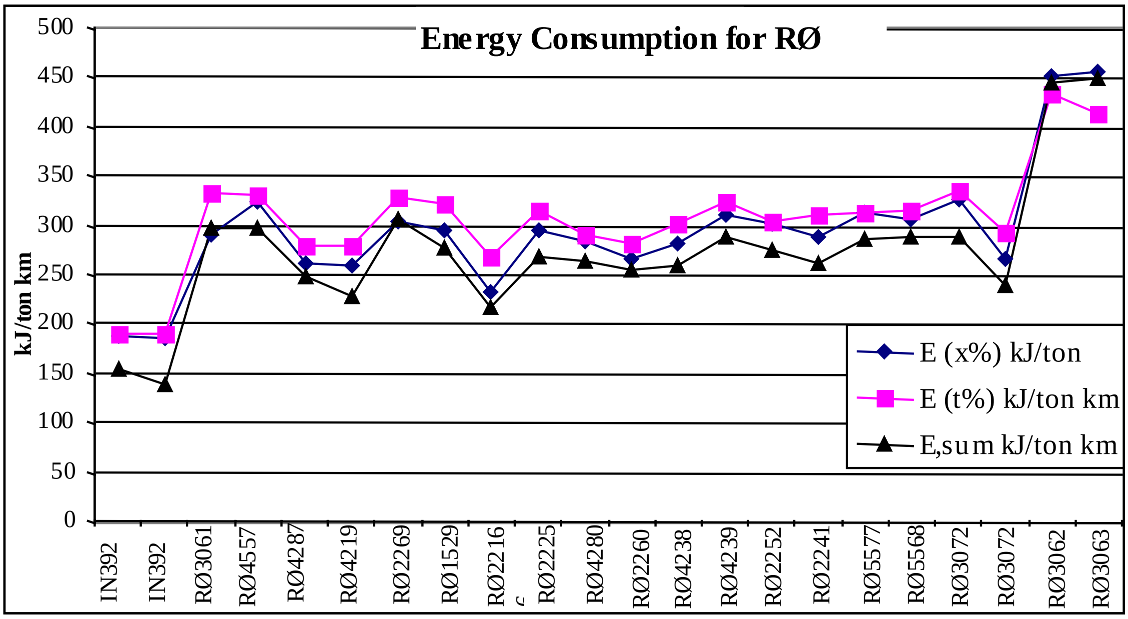
Appendix 20 Simulated energy consumption from Chapter 13.

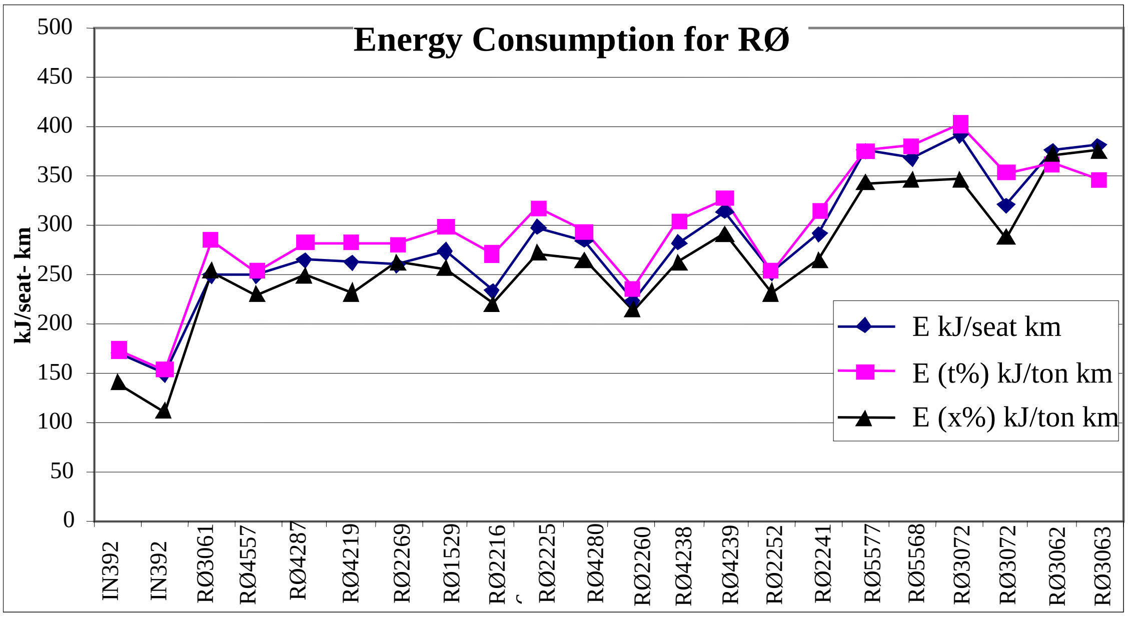


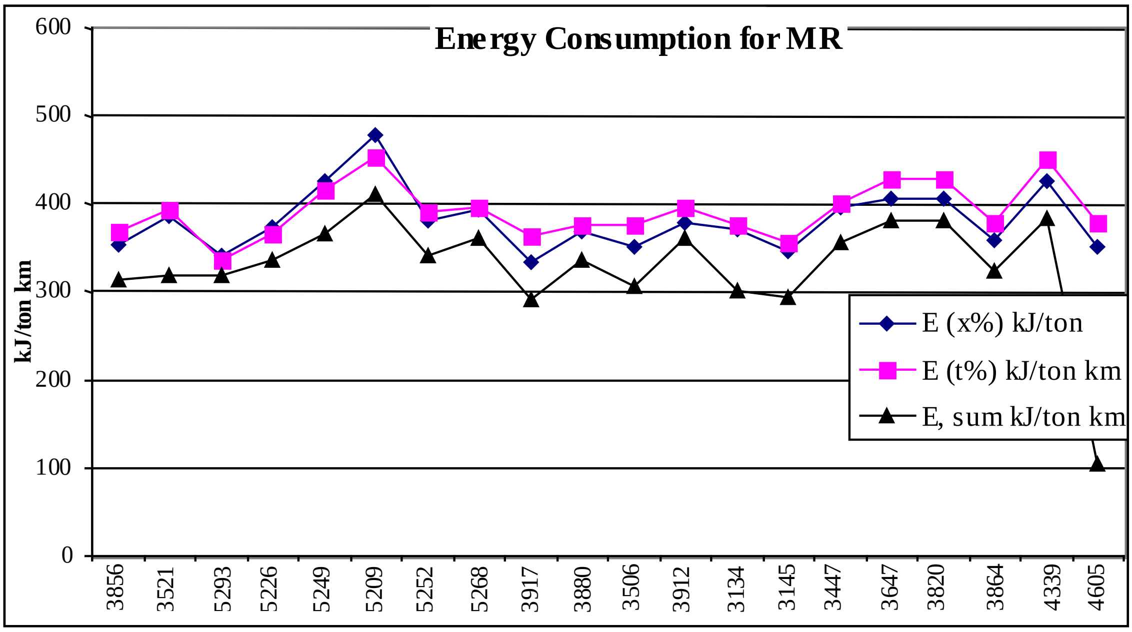


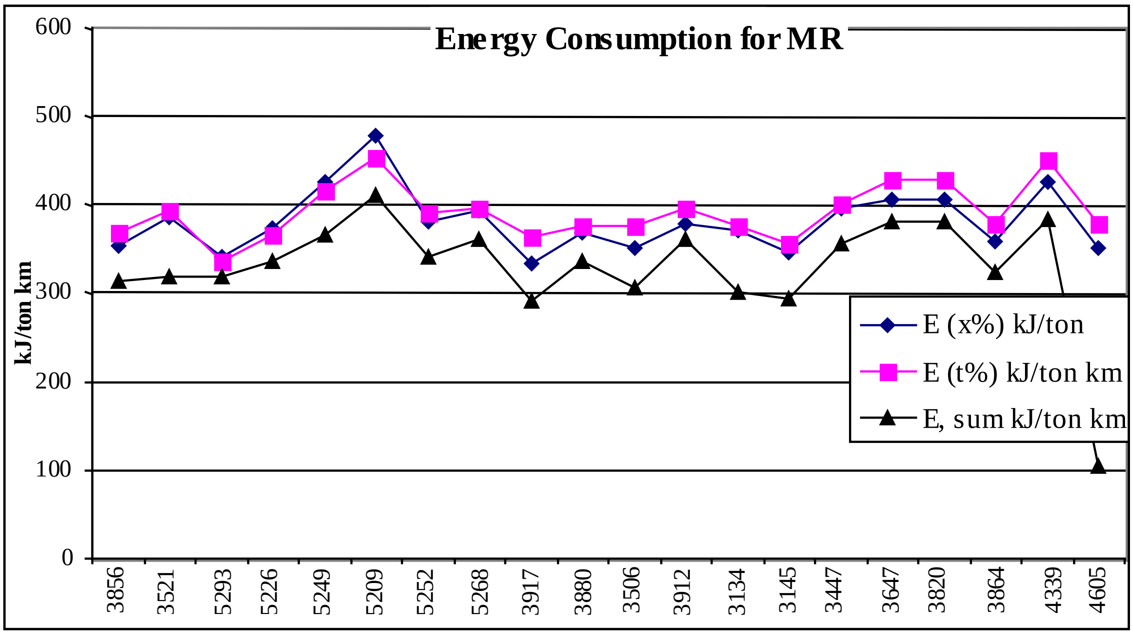

Energy Consumption for ER
kJ/ton km
300
250
200
150
100
50
0
kJ/ton km
E (t%) kJ/ton km
E, sum kJ/ton km
Kh-Od IC917
Od-Kh IC908
Kh-Od IC545
Fa-Kh IC190
Kh-Od IC917
Od-Sø IC917
Sø-Kh IC924
Kh-Od IC957
Od-Sø IC957
Kh-Od IC537
Kh-Od IC28
Od-Fr Re
Fr-Od Re
Od-Fr Re

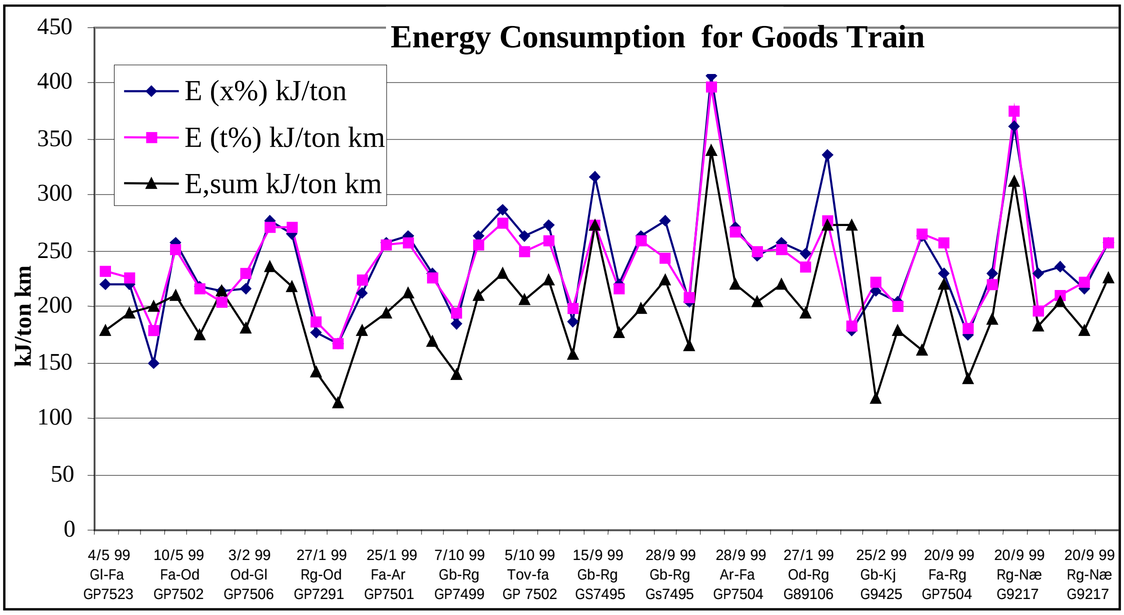

Energy Consumption for ER
kJ/seat km
300
250
200
150
100
50
0
kJ/seat km
E (t%) kJ/seat km
E, sum kJ/seat km
Kh-Od IC917
Od-Kh IC908
Kh-Od IC545
Fa-Kh IC190
Kh-Od IC917
Od-Sø IC917
Sø-Kh IC924
Kh-Od IC957
Od-Sø IC957
Kh-Od IC537
Kh-Od IC28
Od-Fr Re
Fr-Od Re
Od-Fr Re

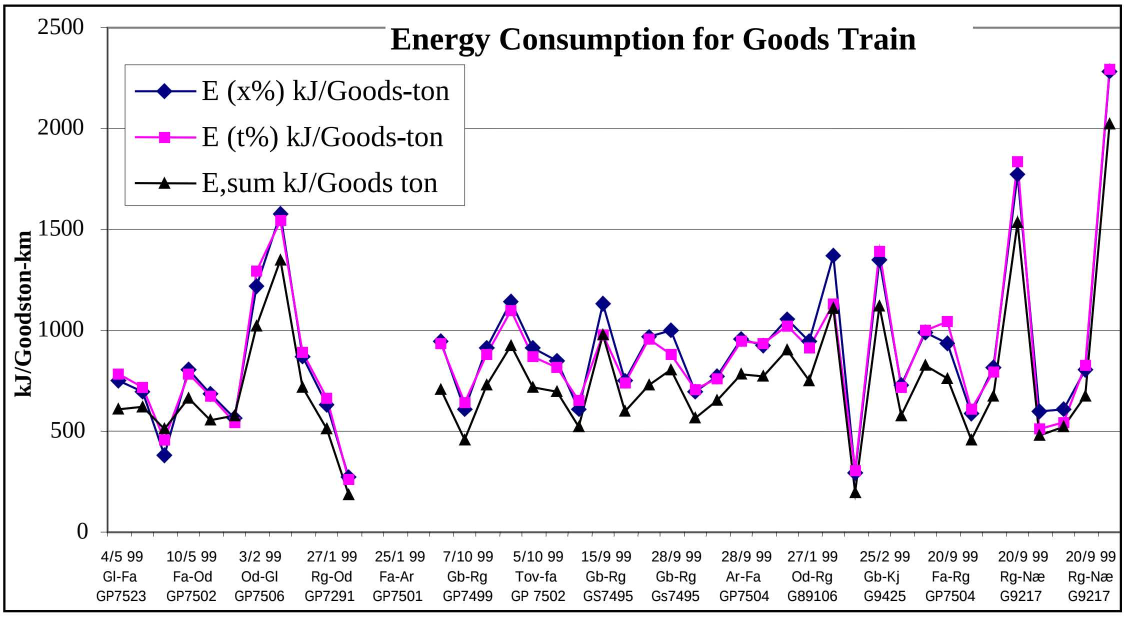

Energy Consumption for RØ
kJ/ton km
500
450
400
350
300
250
200
150
100
50
0
E (x%) kJ/ton
E (t%) kJ/ton km
E,sum kJ/ton km
IN392
IN392
RØ3061
RØ4557
RØ4287
RØ4219
RØ2269
RØ1529
RØ2216
RØ2225
RØ4280
RØ2260
RØ4238
RØ4239
RØ2252
RØ2241
RØ5577
RØ5568
RØ3072
RØ3072
RØ3062
RØ3063


Energy Consumption for RØ
kJ/seat- km
500
450
400
350
300
250
200
150
100
50
0
E kJ/seat km
E (t%) kJ/ton km
E (x%) kJ/ton km
IN392
IN392
RØ3061
RØ4557
RØ4287
RØ4219
RØ2269
RØ1529
RØ2216
RØ2225
RØ4280
RØ2260
RØ4238
RØ4239
RØ2252
RØ2241
RØ5577
RØ5568
RØ3072
RØ3072
RØ3062
RØ3063


Energy Consumption for MR
kJ/ton km
600
500
400
300
200
100
0
3856
3521
5293
5226
5249
5209
5252
5268
3917
3880
3506
3912
3134
3145
3447
3647
3820
3864
4339
4605
E (x%) kJ/ton
E (t%) kJ/ton km
E, sum kJ/ton km


Energy Consumption for MR
kJ/ton km
600
500
400
300
200
100
0
3856
3521
5293
5226
5249
5209
5252
5268
3917
3880
3506
3912
3134
3145
3447
3647
3820
3864
4339
4605
E (x%) kJ/ton
E (t%) kJ/ton km
E, sum kJ/ton km


Energy Consumption for Goods Train
E (x%) kJ/ton
E (t%) kJ/ton km
E,sum kJ/ton km
kJ/ton km
450
400
350
300
250
200
150
100
50
0
4/5 99 Gl-Fa GP7523
10/5 99 Fa-Od GP7502
3/2 99 Od-Gl GP7506
27/1 99 Rg-Od GP7291
25/1 99 Fa-Ar GP7501
7/10 99 Gb-Rg GP7499
5/10 99 Tov-fa GP 7502
15/9 99 Gb-Rg GS7495
28/9 99 Gb-Rg Gs7495
28/9 99 Ar-Fa GP7504
27/1 99 Od-Rg G89106
25/2 99 Gb-Kj G9425
20/9 99 Fa-Rg GP7504
20/9 99 Rg-Næ G9217
20/9 99 Rg-Næ G9217


Energy Consumption for Goods Train
E (x%) kJ/Goods-ton
E (t%) kJ/Goods-ton
E,sum kJ/Goods ton
kJ/Goodston-km
2500
2000
1500
1000
500
0
4/5 99 Gl-Fa GP7523
10/5 99 Fa-Od GP7502
3/2 99 Od-Gl GP7506
27/1 99 Rg-Od GP7291
25/1 99 Fa-Ar GP7501
7/10 99 Gb-Rg GP7499
5/10 99 Tov-fa GP 7502
15/9 99 Gb-Rg GS7495
28/9 99 Gb-Rg Gs7495
28/9 99 Ar-Fa GP7504
27/1 99 Od-Rg G89106
25/2 99 Gb-Kj G9425
20/9 99 Fa-Rg GP7504
20/9 99 Rg-Næ G9217
20/9 99 Rg-Næ G9217

Appendix 21 Example of Black Box Data

For GP7523 Glostrup-Fredericia.

Main data

Litra-Number	:	1505		
V-max	(km/h)	:	140	
Train length	(m)	:	190	
Brake percent	(%)	:	100	
Direction	:	A		
T-Type	:	4		
Wheel dia.	HLOG	(mm)	:	1025
Wheel dia.	ATC	(mm)	:	1025
Date/Time	:	04.05.99	21:29:02	

V-HLOG	V-obs	V-ATC	Traction	Br_pres	Contacts		Route	Tid
km/h	km/h	km/h	Step/kN	Bar	PONMLKJI	HGFEDCBA	m	HH:MM:SS
Date	:	04.05.99						
4	40	1	0	4.9	1010011	10	141930	21:45:04
7	40	1	2	4.9	11	0	141940	21:45:09
9	40	1	2	4.9	11	0	141950	21:45:13
11	40	1	2	4.9	11	0	141955	21:45:14
12	40	12	2	4.9	11	0	141965	21:45:17
14	40	12	2	4.9	11	0	141995	21:45:25
16	40	12	2	4.9	11	0	142045	21:45:36
17	40	16	2	4.9	11	0	142055	21:45:38
15	40	15	3.04	4.9	11	0	142185	21:46:10
16	40	14	3.04	4.9	11	0	142265	21:46:29
19	40	14	3.04	4.9	11	0	142275	21:46:31
20	40	15	3.04	4.9	11	0	142305	21:46:36
22	40	21	3.04	4.9	11	0	142315	21:46:38
24	40	21	3.04	4.9	11	0	142365	21:46:45
27	40	21	2	4.9	11	0	142395	21:46:50
29	40	21	2	4.9	11	0	142445	21:46:56
30	40	29	2	4.9	11	0	142455	21:46:57
31	40	29	1.04	4.9	11	0	142515	21:47:04
32	40	29	0	4.9	11	0	142535	21:47:06
32	40	31	0	4.9	11	0	142845	21:47:41
33	40	32	0	4.9	11	0	143155	21:48:15
33	40	33	0	4.9	11	0	143325	21:48:34
34	40	33	-0.96	4.9	11	110	143335	21:48:35
32	40	33	-0.96	4.9	11	110	143425	21:48:45
29	40	34	-0.96	4.9	11	110	143435	21:48:46
29	40	34	0	4.9	11	10	143445	21:48:48
29	40	33	0	4.9	11	0	143515	21:48:56
29	40	28	0	4.9	11	0	143525	21:48:58
29	40	28	0	4.9	11	0	143545	21:49:00
29	40	28	-0.96	4.9	11	110	143555	21:49:02