Coastdown measurement with 60-tonne truck and trailer

Estimation of transmission, rolling and air resistance

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Preface

On commission of IVL AB, VTI has made a study of driving resistance parameters for a 60-ton truck with trailer. The contact person at IVL AB was Åke Sjödin. This project is included in an implementation program for HBEFA model financed by the Swedish Transport Administration. The contact person at the Swedish Transport Administration was Håkan Johansson. Ulf Hammarström, VTI, has been project leader.

The English translation of this document was controlled by Tarja Magnusson, VTI. We also would like to thank Alltransport AB, and especially Håkan Forsbäck, the truck driver, for good support. Finally we are most grateful to Martin Rexeis at Graz University of Technology for the scientific control of this document.
Quality review

Peer review was performed on 6 February 2012 by Martin Rexeis at Graz University of Technology. Ulf Hammarström has made alterations to the final manuscript of the report. The research director Maud Göthe-Lundgren, VTI, examined and approved the report for publication on 22 March 2012.

Kvalitetsgranskning

Peer review har genomförts 6 februari 2012 av Martin Rexeis at Graz University of Technology. Ulf Hammarström har genomfört justeringar av slutligt rapportmanus. Projektledarens närmaste chef, Maud Göthe-Lundgren, VTI, har därefter granskat och godkänt publikationen för publicering 22 mars 2012.
Innehållsförteckning

Summary ................................................................................................................................. 5
Sammanfattning .................................................................................................................... 7
1 Background ......................................................................................................................... 9
2 Objective ........................................................................................................................... 11
3 A model for driving resistance ......................................................................................... 12
4 Problem description .......................................................................................................... 18
5 Method ................................................................................................................................ 23
  5.1 Introduction .................................................................................................................... 23
  5.2 The test vehicle ................................................................................................................. 23
  5.3 Measurement equipment ................................................................................................. 28
  5.4 The test route .................................................................................................................... 31
  5.5 Measurement procedure for coastdown ........................................................................... 32
  5.6 Meteorological conditions .............................................................................................. 33
  5.7 Measured data ................................................................................................................ 33
  5.8 Examples of driving resistance parameter values from the literature ......................... 38
  5.9 Analysis .......................................................................................................................... 45
6 Results of measurements ................................................................................................. 49
  6.1 Truck with trailer ............................................................................................................ 49
  6.2 Rigid truck ....................................................................................................................... 57
  6.3 Discussion of measuring results ...................................................................................... 60
7 Comparison of measuring results with PHEM data ......................................................... 65
  7.2 PHEM parameter values ................................................................................................. 65
  7.3 Discussion about PHEM parameters compared to the literature and the coastdown study ......................................................................................................................... 71
Discussion on a total level .................................................................................................. 73
Conclusions ......................................................................................................................... 75
List of references .................................................................................................................. 77
List of variables .................................................................................................................... 79

Appendix A Description of test vehicles
Appendix B Tyre tread temperature and pressure
Appendix C Equipment
  1 Road surface quantities measured by the RST vehicle
  2 Driving pattern (VBOX)
  3 Weather station
Appendix D Description of the test route in Linghem
Appendix E Description of the coastdowns
Appendix F  Data set for analysis
Appendix G  Function approaches and estimated parameters
Appendix H  Examples on the use of the estimated function
Coastdown measurement with 60-tonne truck and trailer – estimation of transmission, rolling and air resistance

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Summary

By use of coastdown measurements, driving resistance parameters have been estimated for a truck with trailer (60t) and a box vehicle body. At a vehicle speed of 20 m/s, average meteorological wind conditions and a load factor of 50% the following distribution of the driving resistance components has been obtained:

- transmission resistance (churning losses), 5%
- rolling resistance (test route surface conditions), 41%
- air resistance, 54%.

There are also measurements for the truck without a trailer.

Rolling resistance is dependent on road surface conditions, in particular roughness (iri) and macro texture (mpd). The total rolling resistance consists of three parts: a basic, an iri and a mpd part. The road surface effect amounts to approximately 40% of the total rolling resistance. The iri effect seems to be the dominating part of the surface effects on the contrary to light vehicles.

Comments about estimated parameter values compared to examples from the literature:

- transmission losses: uncertain estimation but at the same level as expected
- rolling resistance, basic part: uncertain estimation but at the same level as expected (Cr0=0.0038 at 5°C)
- air resistance for truck and trailer: considerably higher than expected (Cd0=0.83 and Cdt=0.97 without and with average meteorological wind)
- air resistance for the rigid truck: uncertain estimation but at the same level as expected (Cd0=0.52).

Driving resistance parameters have been estimated by means of regression analysis. A major problem is how to avoid high correlations between explanatory variables. One objective of the experiment design has been to minimize such dependencies.

This study might also be of interest for methodological reasons and in particular for including:

- the introduction of high accuracy road gradients as well as other road surface properties
- the estimation of vehicle mass from coastdown to coastdown
- the equipment (based on Doppler technique) used in order to measure the coastdown driving pattern
- the method used in order to separate parts of the driving resistance.

Driving resistance parameters are used when estimating emission factors for regional and national emission inventories by means of simulation models. In order to reach representative emission factors there is a need for representative driving resistance parameters. This study has demonstrated there could be a considerable underestimation
of simulated truck and trailer air resistance (>50%) in this connection including the drag parameter and cross section area. The drag parameter is considerably higher compared to what is found in literature. This indicates a need for a deeper analysis of different air drag measurement methodologies. If the conclusion of such an analysis will be that the methodology of this study is sound there is a need for extensive coastdown measurements including truck and trailer with the most frequent vehicle body types. Also rolling resistance modelling could need more attention.
Utrullningsprov (coastdown) med 60 tons lastbil och släp – uppskattning av transmissions-, rull- och luftmotstånd

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Sammanfattning

Baserat på så kallad coastdown-mätning har parametrar för färdmotstånd uppskattats för en tung lastbil med släp (60 ton) och med skåp som påbyggnad. Färdmotståndet vid en hastighet av 20 m/s, genomsnittliga vindförhållanden och 50 % lastfaktor fördelas med 5 % på transmissionsmotstånd, 41 % på rullmotstånd och 54 % på luftmotstånd.

Mätningar har också utförts med lastbil utan släp.

Rullmotstånd beror av vägytans ojämnhet (iri) och makrotextur (mpd). Det totala rullmotståndet kan indelas i: basmotstånd (plan yta), motstånd av iri och motstånd av mpd. På mätsträckan utgör vägyteeffekten cirka 40 % av det totala rullmotståndet. Ojämnhetseffekten bedöms utgöra den dominerande delen av vägyteeffekten till skillnad från lätt fordon.

De uppskattade parametervärdena kan jämföras med litteraturen:
- transmissionsförluster, osäker skattning men samma nivå som förväntat
- rullmotstånd, basdelen, osäker skattning men samma nivå som förväntat ($Cr0=0,0038$ vid $5^\circ C$)
- luftmotstånd, lastbil med släp, avsevärt högre än förväntat ($Cd0=0.83$ och $Cdt=0.97$ utan och med medelvind)
- luftmotstånd, bil utan släp, osäker skattning men samma nivå som förväntat ($Cd0=0.52$).

Parametrar ingående i funktioner för färdmotstånd har uppskattats med statistisk analys. Ett problem i detta sammanhang är hur större korrelationer mellan de ingående förklaringsvariablerna skall kunna undvikas. En målsättning i försöksuppläggningen har varit att undvika sådana beroenden.

Föreliggande studie bör kunna vara av metodintresse avseende följande punkter:
- mätsträckans lutning, bestäms med hög noggrannhet (avvägning), och övriga vägtytedata ingår i analysen
- fordonsvikt, uppföljning från utrullning till utrullning
- utrustningen för registrering av utrullningsförloppen (Dopplerteknik)
- separering av olika delar av färdmotståndet.

Färdmotståndsparametrar används för att uppskatta emissionsfaktorer för regionala och nationella inventeringar av utsläpp från vägtrafik. För att uppnå representativa emissionsfaktorer krävs tillgång till representativa parametrar för färdmotstånd. Föreliggande studie har påvisat att det kan finnas risk för en betydande underskattning av luftmotstånd, formkonstant och tvärsnittsarea för tung lastbil med släp (>50 %). Den uppmätta formkonstanten är betydligt högre än vad som framgår ur litteraturen. Detta pekar på ett behov av en djupare analys av de metoder som används för att mäta emissionsfaktorer.
luftmotstånd. Om slutsatsen av en sådan analys skulle bli att metoden som använts i föreliggande studie ger representativa värden finns det behov av att genomföra omfattande utrullningsprov med de vanligaste typerna av påbyggnad. Även modellerna för rullmotstånd skulle behöva mer uppmärksamhet.
1 Background

For estimation of regional and national emissions from road traffic in Sweden a computer model, ARTEMIS/HBEFA, see (Keller and Kljun, 2007), is used\(^1\). This model includes emission factors for different vehicle categories and segments. One such vehicle segment is heavy goods vehicles with a gross vehicle weight of 50–60 ton. In HBEFA per segment there are also separate emission factors for different emission concepts and traffic situations.

For heavy vehicles, emission factors in HBEFA have been estimated by using the simulation model PHEM (Rexeis et al., 2005). Input to this simulation model includes data on a finer level compared to HBEFA.

In principle PHEM simulations include two main input parts: driving patterns and vehicle data. A driving pattern represents one traffic situation and one vehicle category. Vehicle input data includes two main groups: driving resistance and drive train. The drive train includes the engine and the transmission.

Driving resistance includes at least: air resistance, rolling resistance, gravitation resistance and acceleration resistance.

In order to estimate representative emission factors in HBEFA there is a need for both representative driving patterns and vehicle descriptions.

There is continuously an extensive need both of new and old representative data for PHEM simulations of emission factors in HBEFA despite big improvements through the ARTEMIS project.

Because of the harmonized EU legislation vehicle data per segment and emission concept are expected to be equal between the EU countries. However, there are some segments just existing in a few countries. Such segments are HGV 40–50 and 50–60t. If these countries, including Sweden, desire to make these segments as representative as possible they need to contribute for such improvements. In Sweden the HGV 50–60t is a most important segment since for example 2/3 of HGV CO\(_2\) emissions come from this segment.

For the HBEFA purpose there is a need for representative emission factors for vehicles out on the road per vehicle segment and emission concept. This is a major complication especially for heavy trucks with huge variation in vehicle bodies and tyre models. For open platform vehicle bodies the air resistance coefficient and the projected front area will be a function also of the load. In order to estimate representative driving forces out on the road for average vehicles one needs information about the frequency of different vehicle bodies. For each such type of body there will be different drag coefficients and cross section areas. The drag will also depend on whether a trailer is used or not. If drag coefficients are available for some type of bodies there might still be a lack of representative drag parameters depending on the method used for the drag measurement. One further complication about air resistance is meteorological wind.

One method in order to measure parameters for air and rolling resistance is the coastdown method, see for example (Hammarström et al, 2008). One advantage with coastdown is measurements at real conditions. A drawback could be the influence of all

\(^1\) The original name of the program was ARTEMIS. The name has after that been changed to HBEFA.
outdoor factors and the possibility to isolate their influence. At least all such factors with known influence need to be recorded.
2 Objective

Additional input vehicle data for emission factor simulation of 50–60 ton truck with trailer will be estimated primarily based on measurements. These vehicle input data for simulation include parameters for:

- air resistance
- rolling resistance
- transmission resistance.

If possible the air resistance should be estimated as a function of the resulting wind speed and the angle between driving direction and resulting wind in order to make the results more useful. Air resistance parameters include both the drag parameter and the cross sectional area.

The rolling resistance includes at least three parts:

- base resistance at plane and smooth surface ($C_r0$)
- additional resistance for macro texture ($mpd$)
- additional resistance for roughness ($iri$).

In order to compare rolling resistance from different sources, especially the base resistance, these parts should be kept apart if possible. In order to keep them apart one needs to estimate the road surface parameter values.

The objective of this study is both to judge if PHEM input data looks representative and to add new driving resistance parameters for future PHEM simulations if needed.
3 A model for driving resistance

The total driving resistance \((F_x)\) constitutes a sum of forces:

\[ F_x = F_{trm} + F_b + F_{air} + F_{acc} + F_{gr} + F_{side} + F_r \]

- \(F_{trm}\): transmission resistance (N)
- \(F_b\): bearing resistance (N)
- \(F_{air}\): air resistance (N)
- \(F_{acc}\): acceleration resistance from vehicle mass (N)
- \(F_{gr}\): gradient resistance (N)
- \(F_{side}\): resistance caused by the side force (N)
- \(F_r\): rolling resistance (N)

**Transmission resistance:**

At a coastdown situation the gear box is in a neutral position. There will still be churning losses in the transmission oil from the rotation of gear wheels also including the final gear box.

\[ F_{trm} = trm \]

\(trm\): a constant representing the churning losses in the transmission (N)

**Bearing resistance:**

In the wheel bearings there will be a resistance proportional to the vertical force (Mitschke, 1982):

\[ F_b = C_b \cdot F_z \]

- \(C_b\): parameter for bearing resistance
- \(F_z\): vertical load per tyre (N)

**Air resistance:**

The air resistance at calm wind conditions is expressed by:

\[ F_{air} = C_d \cdot A_{yz} \cdot dns \cdot v^2 / 2 \]

where

\[ dns = (348.7/1000) \cdot (Pair/(T+273)) \]

- \(v\): the vehicle velocity (m/s)
- \(dns\): the density of air (kg/m\(^3\))
- \(A_{yz}\): the projected frontal area of the vehicle (m\(^2\))
- \(C_d\): the air dynamic coefficient (dimensionless)
There are different alternatives for including the meteorological wind effect into $F_{air}$:
- with a fixed projected cross area (I)
- with a cross area orthogonal to the resulting wind (II).

Alternative (I):

$$F_{air} = C_d0*(1+C_d1*\sin(b))\cdot \cos(b)\cdot Ayz\cdot dns\cdot vlr^2/2$$

$vlr = (v^2 + 2 \cdot v \cdot vl \cdot \cos(a) + vl^2)^{0.5}$

$b = \arccos((v + \cos(a) \cdot vl)/vlr)$

$fxl = \cos(b)\cdot vlr^2\cdot Ayz\cdot dns/2$

$Ayz$: the projected front area ($m^2$)

$vl$: meteorological wind speed (m/s)

$vlr$: resulting wind speed from meteorological wind and vehicle speed wind (m/s)

$a$: angle in the interval 0 to π between vehicle length axis and $vl$ (rad)$^2$

$b$: angle (yaw) in the interval 0 to π between vehicle length axis and $vlr$ (rad)

$fxl$: a help variable in order to simplify the work with the parameter estimation

$C_d0$: is the air dynamic coefficient when $b=0$

$C_d1$: adjustment parameter for resulting wind direction deviating from direction of speed wind

The side wind approach including the sinus function is not based on the literature.

Alternative (II):

$$F_{air} = C_d0*(1+C_d1\cdot\sin(b))\cdot \cos(b)\cdot A(b)\cdot dns\cdot vlr^2/2$$

$A(b)= \cos( b)\cdot AYZ + \sin( b) \cdot AXZ$

$Ayz= h \cdot b$

$Axz= h \cdot L$

$C_d1\cdot$: adjustment parameter for resulting wind direction deviating from direction of speed wind and a projected area orthogonal to resulting wind.

---

2 If $a>\pi$ then $a=2\pi-a$, else $a:=a$. 

\( A(b) \): the vehicle cross section area orthogonal to resulting wind at yaw equal to \( b \).

\( Axz \): the projected side area (m\(^2\))

\( h \): the height of the the truck or the truck with trailer (m).

\( L \): the length of the the truck or the truck with trailer (m).

In this case (II) the change in projected area with the yaw angle \( b \) will not be included in \( Cd \). \( Cd \) will only include the aerodynamic change with \( b \).

The values estimated from coastdown measurements include two effects of meteorological wind:

- a change in average resulting wind
- a change in \( Cd \) depending on a change in the angle between resulting wind and the driving direction.

The isolated wind effect factor is expressed by the quote:

\[
\text{Isolated wind effect factor: } \cos(b) \frac{vl^2}{vlr^2}
\]

The true wind effect for a time period is the average value of this quote for all \( v \), \( vl \) and \( a \) for the time period of interest. In this study the estimation of this effect has been simplified to a uniform distribution of \( a \). The effect then is estimated for different combinations of \( v \) and \( vl \). This effect is always possible to include in air resistance estimation even if there is no information about \( CdI \).

The meteorological relative wind effect on \( Cd \) is possible to describe in a similar way as the isolated wind effect:

\[
\text{Wind effect on } Cd: \ (1+CdI \sin(b))
\]

The angle \( b \) is a function of \( v \), \( vl \) and \( a \). The effect asked for is an average value of the expression for the time period of interest. An alternative is to estimate the effect for different combinations of \( v \) and \( vl \) at a condition of a uniform distribution of \( a \) around the horizon.

The two wind effects described above could also be integrated to one value:

\[
CdI= Cdo(1+CdI \sin(b)) \cos(b) \frac{vl^2}{vlr^2}
\]

In the literature there might be a problem to find out what is included in a “\( Cd \)” value:

**Inertial force:**

\[
Facc=macc \frac{dv}{dt}
\]

\[
macc=m+m_J
\]

\( \frac{dv}{dt} \): the acceleration level (m/s\(^2\))

\( m \): the total mass of the vehicle (kg)

\( m_J=\text{sum}(K_J \frac{J}{rwh^2}) \), where sum means summation over the wheels (kg)

\( rwh \): the wheel radius (m)

\( J \): the inertial moment per wheel (kgm\(^2\))
$K_J$ (set to 1.0 in this study): a correction factor of $J$ to include moving parts in the transmission system.

**Gradient resistance:**

$F_{gr} = m * 9.81 * \sin(gr)$

where

$gr$ is the longitudinal slope (rad)

**Side force resistance:**

$F_{side} = F_y * Cr3$

where

$F_y = m * (\cos(crf/100) * v^2 / R - 9.81 * \sin(crf/100) * \cos(gr))$

$Cr3 = 1 / CA$

- $F_y$: the side force acting on the vehicle (N)
- $CA$: the tyre stiffness parameter (N/rad)
- $Crf$: the crossfall (%)
- $gr$: the longitudinal slope (rad)
- $R$: the radius of the road curvature (m)
- $Cr3$: the estimated parameter for the stiffness inverse (rad/N)

The cross fall of the road will influence the force distribution from left to right. Higher vertical force on the right side is expected to give higher tyre temperature and pressure on the right hand side of the vehicle.

The cross fall causes a driving resistance ($F_{side}$) because the tyre will not be parallel to the vehicle movement direction. $F_{side}$ is a function of $CA$. $CA$ is a non-linear function of the tyre load. Because of the cross fall one can expect different $F_{side}$ on different wheels on the same wheel axle. This level of detail has not been used in the analysis.

**Rolling resistance:**

The following basic model will be used in this report.

$F_r = Cr * m * 9.81$

There are several alternatives to express $Cr$ as a function of other variables. The following alternatives will be tested in this study:
**Road surface conditions**

\[ Cr = Cr_0 + iri*(Cr_{10} + v*Cr_{11}) + mpd*Cr_{20} \]

where

- \( iri \): the road roughness measure (mm/m)
- \( mpd \): the macrotexture measure (mm)
- \( m \): the vehicle mass (kg)
- \( v \): the vehicle velocity (m/s)
- \( Cr_0, Cr_{10}, Cr_{11} \) and \( Cr_{20} \): the parameters for estimation.

**Ambient temperature**

\[ Cr = Cra*(1+Crb*T) \]

where

- \( T \): the ambient temperature (°C)
- \( Cra \) and \( Crb \): the parameters for estimation.

\( Cr \) is expected to depend on tyre temperature. The tyre temperature is expected to depend on several variables including the ambient temperature.

**Wheel load**

There is information in the literature (Rexeis et al., 2005) about \( Cr \) being a function of the normal force \( F_z \) per tyre:

\[ Cr = Crz_0 + Crz^{1'*}F_z \]

or

\[ Cr = Crz_0 + Crz^{1''*}rF_z \]

\[ rF_z = F_z/F_{zmx} \]

where

- \( F_{zmx} \) is the maximum allowed load per tyre (N)
- \( rF_z \) is the relative load per tyre (N/N)
- \( Crz_0 \), \( Crz^{1'} \) and \( Crz^{1''} \): the parameters for estimation.

This means that the rolling resistance (N) depends with a squared form on \( F_z \).
Vehicle speed

\[ Cr = Cra + Crb \cdot v \]

\( Cra \) and \( Crb \) are parameters for estimation.

Parallel variables in rolling resistance

These proposed models for different variables can be criticized for not including all explanatory variables at the same time. It is not obvious how to formulate a model including all these variables in parallel. Even if such a total model could be formulated there might be problems with the parameter estimation. As a first step these variables can be treated one at a time.
4 Problem description

The potential problems in general when measuring and estimating driving resistance based on road measurements include:

- which explanatory variables to include and how to record them with good accuracy
- how to model driving resistance
- how to separate rolling resistance, transmission losses and bearing losses
- how to avoid correlations between explanatory variables in general
- how to chose when more than one measure exist for the same type of road surface condition
- changes in the test vehicle during a day and between days
- the need for control and adjustment of tyre pressure
- variation in road surface conditions across the road, introducing an uncertainty concerning which conditions the test vehicle tyres have been exposed to
- how to compare with the literature.

The explanatory variables to include in the model should primarily be:

- those with more than minor effects on total driving resistance
- those of special interest for emission factor simulation.

In principle all variables described in section 3 are judged being of importance. There are also some additional variables of interest.

Some variables are of interest both in order to give a possibility to present results for a reference situation and for estimation of representative driving resistance out on the road in general. One purpose of using such variables is to make measured data under different conditions presented in the literature comparable. Ambient temperature could be such a variable.

If variables of importance for driving resistance are not included in used functions these effects will still be there but hidden in the parameter values that are present. Such a result will then cause problems when trying to compare results in this study with results in the literature.

What variables to include and how to model driving resistance is to some extent expressions for the same problem. In order to estimate reliable parameter values the function approach used need to be representative. There are no doubts how to model $F_{acc}$ and $F_{gr}$. All other expressions for part resistances presented in section 3 are more or less possible to be questioned.

The need for HBEFA, estimation of emission factors by the use of the PHEM model, is a general driving resistance model for all types of road vehicles and all tyre models used per vehicle type. Road surface conditions are not of interest in HBEFA except that the rolling resistance should be representative for average road surface conditions. Results about road surface effects are available in the literature mainly for cars. In order to estimate rolling resistance coefficients representative for average road surface conditions the conclusion then must be a need for a rolling resistance model including road surface effects. If there are more than minor differences about road surface conditions between different EU countries there is a need for special correction factors.
There is a need to develop a general tyre model based on the literature and own measurements. General problems include:

- the rolling resistance differs between tyre models of the same dimension
- the rolling resistance differs between tyres of different dimensions
- the rolling resistance changes as a function of a change in tread depth
- the rolling resistance differs between freely rolling and drive wheels
- the rolling resistance, if roughness effects are included, is different for different vehicles for the same set of tyres
- the rolling resistance effects from variables described in section 3 might depend on the preceding variables.

All tyre properties expressed by the parameters in section 3 are of budget reasons not possible to measure even for the most frequent tyres in the vehicle fleet. At best one could expect that Cr0 in general is available. One important question therefore is in what way the other tyre parameters will change for variation in Cr0.

There is a problem to separate rolling resistance, transmission resistance and bearing resistance. The rolling resistance increases with increasing vehicle weight and the oil rotating losses are independent of vehicle weight. By varying the vehicle weight it should be possible to separate transmission resistance from rolling and bearing resistance.

Transmission resistance includes two parts: mechanical losses between the gear-wheels and oil rotating losses. During coastdown with the gear box in neutral position there is essentially one part present: the oil rotating losses.

Bearing resistance is a function of vertical load and will not be possible to separate from rolling resistance by coastdown measurements.

The need for isolating different parameters for rolling resistance, for air resistance etc. is an expression for the need of a general driving resistance model. If there only were a need for a driving resistance model for the measuring vehicle at one load level it would be enough with one second-degree polynomial of vehicle speed without a trial to isolate rolling resistance etc.

In this study, measurements represent different modes:

- with or without trailer
- with or without load.

If each mode is measured at only one occasion there will be different weather conditions per mode. In order to handle this problem, i.e. a risk for high correlations between meteorological variables and other explanatory variables, each mode should if possible be measured at least at two different occasions.

Especially for the road surface there exist several measures for the same type of characteristics. In (Hammarström et al, 2008) several measures were recorded in...
parallel. It turned out that $iri$ and $mpd$ were the measures with the highest degrees of explanation in order to describe the resistance contribution from roughness and macro texture for a car. However, there still are questions about these measures:

- **$iri$**: when the unevenness wavelengths decrease below 2 m at constant amplitude $iri$ will decrease but the damping losses in shock absorbers and in the tyres will increase (Hammarström, 2000)

- **$mpd$**: the $mpd$ value can be an expression for a negative (deviations mainly downwards) or a positive (deviations mainly upwards) macro texture. One plausible hypothesis then would be that a positive texture has a higher rolling resistance than a negative one for the same $mpd$ value.

There is a possibility that the type of road surface measures with the highest degree of explanation for rolling resistance is dependent both on the contact area dimensions and on other vehicle parameters. One hypothesis could be that the length of the contact area is of importance for the wavelengths to include in macro texture and roughness. For the same vehicle the contact area will change with vehicle load and consequently also the wave length limits for “macro texture” and “roughness”.

Rolling resistance is a function of the road surface conditions: macro texture ($mpd$), roughness ($iri$) and conditions caused by the weather conditions. If these contributions to the rolling resistance can not be isolated, the resulting estimated rolling resistance will be typical for only the road surface conditions at the road section included in this study. The road surface conditions for the test route are measured with high accuracy. If it is possible to isolate for $iri$ and $mpd$ the base rolling resistance parameter ($Cr0$) will represent a completely smooth and even road surface.

Even if one uses standardized measures for road surface conditions with high degree of explanation for driving resistance, problems can follow from the variation in conditions across the road. Standardized road measures for road surface conditions represent just special positions across the road:

- **$iri$** is measured in two tracks: one in the left rut and one 1.5 m to the right
- **$mpd$** is measured in three tracks: one in the left rut, one 1.5 m to the right and one between

The width between the tyres per axle is for a 60 t vehicle more than 2 m. The impact of the road surface conditions on the motion of the vehicle will depend on the side position of the vehicle and the width between the wheels on the left and right side of the test vehicle. For heavy vehicles with four wheels on the rear axle there will be a difference between road condition exposure for the wheels on the front and rear axle. There will also be different exposure for the truck and the trailer depending on different average widths between the wheels. If rolling resistance effects are estimated based on measurements in an ideal situation the side location for each wheel and the road conditions in these positions should be known along the test route.

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3 Evaluated measures in ECRPD (wave length interval): $FRMS$ (0.002-0.01m); $mpd$ (0.001-0.100 m); $iri$ (0.25- m); $RMS1$ (0.5-1.0 m); $RMS2$ (1.0-3.0 m); $RMS3$ (2.0-10.0 m); $RMS4$ (10-30 m) and $RMS5$ (0.5-30 m) (Hammarström et al, 2008)
There will be continuous changes of the test vehicle during measurements at least for the vehicle weight. Even if the change of the amount of fuel in the tank is not big compared to total GVW there still is a systematic variation by time. This effect is possible to control with small efforts.

Other properties not easy to control and adjust for are the braking system and tyre conditions. Tyre conditions include tyre wear, tyre temperature and tyre pressure. During a measuring program there could be a total driving distance of for example 1 000 km. The rolling resistance is expected to decrease with increasing tyre wear. Even if 1 000 km will cause just most marginal wear there will be an effect.

The test vehicle represents a part of the measuring system. The measuring system may not vary by time, at least not out of control. Using coastdown measurements, compared to using fuel consumption measurements, should reduce the risk for a change in the measuring system by time since the influence of the engine and a variation in fuel qualities are excluded. Before start of measurements the test vehicle needs to be fully warmed up at a stabilized level. Not only the tyres but also the transmission etc. need to warm up.

One main problem when measuring rolling resistance is how to handle tyre pressure. Increasing tyre pressure reduces rolling resistance. Tyre pressure is a function of:

- air pressure: increasing air pressure will decrease tyre over pressure
- air temperature: increasing air temperature will increase tyre pressure
- rolling resistance: increasing rolling resistance will probably increase tyre temperature and tyre pressure.

These changes will be expected during measurements if there are no adjustments of the tyre pressure.

Tyre temperature is not only of importance for tyre pressure but also directly for rolling resistance.

The amount of load can influence tyre pressure in two ways:

- Increasing load will probably increase tyre temperature which will increase tyre pressure
- There is a possibility that a change of load influences tyre pressure at stand still, at the same tyre temperature. The interest of such an effect is useful for control and adjustment of tyre pressure at change of load.

One further point of interest for the test design is how to handle if there might be a tyre air leakage.

The study includes coastdowns at different occasions and with two load levels. Possible alternatives for tyre pressure adjustments:

- adjustments for leakage only
- adjustments for all deviations from desired pressure
- adjustments for change of load.

---

4 Tyre pressure = Total pressure – ambient air pressure
The first alternative means that there will be different tyre pressures for different parts of the measurements as a function of ambient temperature and air pressure variations even if there is no leakage. In order to handle the control problem there is a need for modelling of tyre pressure changes to find the control pressure, the pressure there should be without a leakage. In practice this alternative is difficult to fulfil.

In (Hammarström et al., 2008) the tyre pressure was adjusted to the same level before entering each test route, the second alternative above. Since the test routes had different surface properties the tyre temperature and the tyre pressure changed from test route to test route even if the initial pressure per test route was kept constant.

Estimated rolling resistance should be representative for normal use of road vehicles. The instruction to the driver for tyre pressure adjustment is for "cold" tyres. One could expect that there is a time period of at least some weeks between tyre pressure adjustments during normal use. When studying the influence of load on tyre pressure there also is a behavioural aspect concerning the driver. What is typical: to adjust tyre pressure for the load or not?

Frequent controls and adjustments of tyres on a truck with trailer are most time consuming to perform.

Driving resistance parameters in the literature represent different conditions.

The rolling resistance is higher for driving wheels than for freely rolling wheels, see (Gent and Walter, 2005). Road surface effects estimated from fuel consumption measurements include a mix of freely rolling wheels and driving wheels while coastdown measurements only include free rolling wheels.

If rolling resistance is measured in a laboratory, the measured wheel in general is run on a drum or on a roller. The measured values, if used for simulation, need to be adjusted to represent a flat surface. This might be a problem when using or comparing with data in the literature; some are adjusted and others are not. If the measuring conditions including the drum diameter are documented the presented \( Cr0d \) can be adjusted to represent a flat surface \( (Cr0) \). However, the accuracy of these adjustment functions for tyres in general are unknown to VTI.

Based on measurements with just one vehicle in this study there is an objective to judge how representative parameter values used in PHEM simulations are and to estimate more representative parameters values if possible. In combination with values in the literature it should at least be possible to judge if PHEM values are representative or not.
5 Method

5.1 Introduction

The method used in this study was mainly developed in a previous study, see (Hammarström et al., 2008). Compared to the previous study the main changes are:

- the way to record the driving pattern
- the way to record meteorological data
- the way to measure road gradient
- the way to separate transmission resistance and rolling resistance.

5.2 The test vehicle

The test vehicle used:

- truck and trailer
- truck: Volvo FH16
- gross vehicle construction weight: truck, 27 t; trailer, 36 t
- gross vehicle road weight, 60 t in total
- total length of the truck with trailer: 24 m
- empty weight: truck, 13.1 t; trailer, 10.1 t
- vehicle body for both truck and trailer: box
- roof spoiler for air resistance reduction on the truck
- height for the truck and the trailer: 4.35 and 4.45 m respectively
- distance from the rear end of the truck box to the front end of the trailer box, 1.70 m
- suspension system: leaf springs on the truck and air suspension on the trailer (in neutral position)\(^5\)
- number of axles: truck, 3; trailer, 4
- number of tyres: truck: 2-4-2; trailer: 2-2-2-2 (super single on the trailer)
- year model of the truck: 2007
- emission concept: euro 4.

The third axle on the truck has been in down position, in contact with the road surface, for all measurements.

A more detailed description of the test vehicle is presented in Appendix A.

The operative weight of the vehicle will change continuously during the measurements, i.e. vary from one coastdown to another depending on the amount of fuel in the tank. The maximum amount of fuel in the tank is 610 dm\(^3\). The lowest value during measurements has been 410 dm\(^3\). The amount of fuel in the tank is estimated per coastdown and used for the total mass estimation.

The weight per each coastdown has been estimated and used in the analysis, see table E1–E4.

The weight of the vehicle combination has been measured at two occasions: empty vehicle and loaded vehicle, see table A5.

\(^5\) “For this type of vehicle air suspension on the trailer is the most frequent alternative”. Information from Håkan Forsbäck, the truck driver (2011-02-25).
The objective has been to use a type of heavy truck vehicle body as common as possible in real traffic. Data from 1997 is available describing mileage for rigid truck (RT) and truck with trailer (TT/AT). Each such group is possible to split after type of vehicle body. In the group of heavy trucks and trailer with GVW>50 t mileage has been split after vehicle body (for the truck), see table 5.1.

Table 5.1 Distribution of mileage for HGV>50 t on type of body (1997).*

<table>
<thead>
<tr>
<th>Body type for the truck</th>
<th>Year model</th>
<th>Total%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt;= 92</td>
<td>93–95</td>
</tr>
<tr>
<td>Open platform</td>
<td>28.9</td>
<td>29.8</td>
</tr>
<tr>
<td>Bunks</td>
<td>8.7</td>
<td>8.9</td>
</tr>
<tr>
<td>Platform, covered</td>
<td>3.9</td>
<td>2.5</td>
</tr>
<tr>
<td>Box</td>
<td>30.6</td>
<td>28.6</td>
</tr>
<tr>
<td>Tank</td>
<td>15.4</td>
<td>13.8</td>
</tr>
<tr>
<td>Others</td>
<td>12.6</td>
<td>16.5</td>
</tr>
<tr>
<td>Total</td>
<td>100.0</td>
<td>100.0</td>
</tr>
</tbody>
</table>

*Tractor and trailer are not included.

Probably a substantial part of “open platform” and “others” in practice also are covered vehicles.

For rolling resistance the tyres used on the test vehicle are of interest. In Appendix A there is a detailed specification of test vehicle tyres. Conditions of special interest:
- super single tyres on the trailer and ordinary tyres on the truck
- a mix of different tyre dimensions on the truck, see table A3
- in total tyres from four different manufacturers, see table A3
- tyre tread depth, see table A4
- one tyre on the trailer was changed between first and second day of measurements.

The objective for tyres used in measurements was that they should be as common as possible on road vehicles.

The tyres on the test vehicle can be compared to observed frequencies of tyre type on trucks and trailers in general. Observed frequencies on parked trucks:
- Michelin 46%
- Dunlop 17%
- Kumho 9%
- Goodyear 5%

---

6 A data set used for (Hammarström and Yahya, 2000) has been analyzed further in order to estimate the distribution of mileage on different vehicle bodies.

7 Observations on parking spots in Linköping and Norrköping 2009 in the VTI project “Produktionsmätning av rullmotstånd”.
Of 16 tyres in total on the test vehicle:
- 2 Michelin (12.5%)
- 8 Dunlop (50%)
- 4 Kumho (25%)
- 2 Yokohama (12.5%).

There have been two load conditions for the test vehicle: empty and approximately half loaded (20.4 t or \( l_f = 57\% \)). In figure 5.1 and 5.2 the position of the load is described.

*Figure 5.1  The position of the load in the truck.*
The tyre pressure is of importance for rolling resistance. The intention has been to set tyre pressure at stabilized tyre temperature conditions. Setting of tyre pressure:

- driving axle: 7.5 bar
- other axles: 9.0 bar.

The tyre pressure needs to be adjusted to the specified pressure levels at least in the beginning of each measuring day. At the end of each day the pressure needs to be controlled.

For all measurements of tyre pressure there have been measurements of tyre temperature in parallel. The tyre temperature also needs to be measured for systematic changes in measuring conditions like with and without trailer, different load conditions etc. The tyre temperature, the ambient temperature, and the air pressure can be used to estimate missing tyre pressure values.

Measured tyre pressures are presented in table B1–B3 and measured tyre temperatures in figure B1–B6. In table 5.2 average tyre temperature and average pressure values are presented.
Table 5.2 Tyre temperature and tyre pressure at coastdowns for truck and trailer.

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Odometer</th>
<th>Ambient temperature</th>
<th>Air pressure</th>
<th>Tyre temp.***</th>
<th>Tyre pressure***</th>
<th>Comment*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(°C)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(mbar)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(°C)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(bar)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Without load</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14/10</td>
<td>15.50</td>
<td>341571</td>
<td>5.0</td>
<td>1019,5</td>
<td>14,4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14/10</td>
<td>16.43</td>
<td>341614</td>
<td>5.0</td>
<td>1019,5</td>
<td>15,5</td>
<td>No trailer</td>
<td></td>
</tr>
<tr>
<td>14/10</td>
<td>17.30</td>
<td>341646</td>
<td>4.5</td>
<td>1019,5</td>
<td>12,9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>With load</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21/10</td>
<td>9.30</td>
<td>343404</td>
<td>1.5</td>
<td>1013</td>
<td>5,8</td>
<td>8,2</td>
<td>Pressure control</td>
</tr>
<tr>
<td>21/10</td>
<td>10.30</td>
<td>343404</td>
<td>2.1</td>
<td>1013</td>
<td>5,8</td>
<td>8,6</td>
<td>Adjustment;</td>
</tr>
<tr>
<td>21/10</td>
<td>12.43</td>
<td>343448</td>
<td>3.4</td>
<td>1013</td>
<td>13,9</td>
<td></td>
<td>Wet/moist**</td>
</tr>
<tr>
<td>21/10</td>
<td>12.55</td>
<td>343457</td>
<td>3.8</td>
<td>1013</td>
<td>13,7</td>
<td></td>
<td>Wet/moist**</td>
</tr>
<tr>
<td>21/10</td>
<td>14.12</td>
<td>343520</td>
<td>4.2</td>
<td>1013</td>
<td>13,4</td>
<td></td>
<td>Wet/moist**</td>
</tr>
<tr>
<td>Without load</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21/10</td>
<td>15.38</td>
<td>343554</td>
<td>4.8</td>
<td>1012,0</td>
<td>13,8</td>
<td>9,1</td>
<td>Pressure control</td>
</tr>
<tr>
<td>21/10</td>
<td>16.41</td>
<td>343580</td>
<td>5.4</td>
<td>1012,0</td>
<td>14,5</td>
<td></td>
<td>Moist**</td>
</tr>
<tr>
<td>21/10</td>
<td>18.00</td>
<td>343646</td>
<td>5.6</td>
<td>1012,0</td>
<td>14,0</td>
<td></td>
<td>Moist**</td>
</tr>
</tbody>
</table>

*With trailer if nothing else is stated; **The wet or moist road surface was caused by high humidity i.e. not by rain; ***Measured average values for all tyres. The averages with and without trailer are not comparable.

At measurements 14/10 practical problems with a tyre valve caused that there were no tyre measurements and no settings of tyre pressure.8

At measurements 21/10 the tyre pressure was handled as follows:
- Measurement of tyre pressure for all tyres before adjustment, loaded vehicle
- Adjustment of tyre pressure: 7.5 and 9.0 bar respectively before coastdown, loaded vehicle
- Measurement of tyre pressure for all tyres after unloading and before measurements with unloaded vehicle.

Because of technical problems with tyre valves 21/10 the pressure settings were delayed and the pressure was adjusted at a tyre temperature below a driving stabilized temperature level. After adjustment and conditioning the tyre temperature stabilized at a level of approximately 10.5 °C above the ambient temperature. After unloading and new conditioning the average tyre pressure was 0.5 bar above the desired pressure. The tyre pressure during coast downs 21/10 is estimated to be approximately 0.5 bar above the desired pressure level.

8 14/10 one valve was broken but without leakage. 21/10 one valve was broken including leakage.
The wet road surface does not seem to have influenced the tyre temperature and probably not the tyre pressure either.

Based on ambient temperature, tyre temperature, air pressure and tyre pressure 21/10 the tyre pressure 14/10 has been estimated to be approximately marginally below the adjustment average level (the desired level)\(^9\). The resulting effect then would be that the tyre pressure during coastdowns at 14/10 can be closer to the desired level than at 21/10. The difference in pressure is estimated to be approximately 0.5 bar.

For rolling resistance the tread pattern depth is expected to be of importance. In table A4 the measured depth of the tread pattern per tyre is presented.

### 5.3 Measurement equipment

For registration of the **driving pattern** in the coastdown an equipment VBOX 3i from Racelogic has been used, see Appendix C. VBOX measures speed and distance with a frequency of 100 Hz based on GPS. Speed is measured based on Doppler technique. Accelerometers are used in cases when the number of satellites in contact is insufficient. The equipment includes an antenna which has been mounted on the roof in the front of the truck box.

In order to **connect the driving pattern with the road conditions**, especially the gradient, there is a demand for high accuracy in the positions of the coastdown vehicle. In order to reach the desired accuracy a photo sensor on the vehicle is used. At the start coordinate and the end coordinate of the test route there is a reflector.

The registration of **weather conditions** is based on the following sources:

- 14/10: meteorological stations at Malmen airport and a VVIS station at road E4
- 21/10: one weather station placed close to the test route, see figure 5.3. The height of the wind speed recorder was 1.5 m. Also data from Malmen and VVIS have been used.

\(^9\) There were no tyre pressure adjustment between 14/10 and 21/10 with exception for the replaced tyre.
Figure 5.3 Location of the meteorological station (21/10).

In order to have comparable wind speed data for the two days, recorded wind speeds in parallel at 21/10 from the different equipments were compared. Based on these data, observed wind speed from 14/10 was adjusted to be representative for the equipment used 21/10.

For **tyre temperature measurements** an infrared temperature measuring unit has been used. Temperature was measured in the centre of the tyre tread.

**Tyre pressure** was measured with equipment at a tyre company in Linköping.

**The Road Surface Tester (RST)** has been used in order to measure road conditions with exception for the road gradient, see picture 5.4.

Figure 5.4 The RST (Road Surface Tester) research vehicle is a multi-functional instrument.
Description of the RST:  

“Every variable can be measured simultaneously or independently. All measurements are made at normal traffic rhythm.

The variables are calculated and displayed in real time. Normally average data are stored and displayed every 20 metres, although this is adjustable from 5 metres upwards. Raw data can be collected if necessary. The results are produced in a well-defined file format. Alternatively VTI can analyse the data and deliver the results in the form of a report.

Cross profile

Cross profile is measured with the aid of up to 19 lasers and has a measuring width of 3.65 metres. Rut depth is calculated from the cross profile in accordance with the wire principle, both for the entire profile and for the right and left part.

Crossfall

The crossfall of the cross profile is measured as the inclination of the regression line for the cross profile and as the inclination of a fictitious line through two of the outermost lasers on each side.

Curvature

Curvature describes the mean curvature of the vehicle’s line of travel.

Longitudinal profile

Longitudinal profile is measured simultaneously in the left and right wheel track. At the same time, calculations are made of various roughness parameters such as IRI (International Roughness Index) and RMS values for six different wavelength bands. This function of the RST was not used at Linghem test route.

Texture

Macrotexture and megatexture are measured simultaneously in the right wheel track and in the centre of the carriageway.”

Additional RST information for the Linghem test route:

- average data for 20 m sections
- roughness: two detectors; one for the left wheel track and one for the right wheel track; distance between left and right, 1.50–1.52 m.
- macro texture: three detectors; one for the left wheel track, one for the right wheel track and one between; distance between left and right, 1.50–1.52 m.

The positions for $iri$ and $mpd$ measurement are a deficiency in order to estimate the influence on rolling resistance for a heavy truck. A distance of about 2 m would have been more representative in order to describe road surface effects for heavy trucks. One further deficiency is the width of each measured $iri$- and $mpd$ track, just 0.5 mm. A width equal to the tyre width should increase the probability for measured road surface values being representative for tyre exposure.

10 http://www.vti.se/templates/Page____3255.aspx
The road surface measures by RST, measured per 20 m intervals, can be summarized as follows:

- road roughness (iri)
- texture (mpd)
- crossfall (%)
- rut depth (mm).

In the ECRPD study the big importance of gradient data with high accuracy was demonstrated. In order to fulfil this demand gradients, altitude, were measured with levelling technique per 10 m. The gradient in between these 10 m observations was measured with laser equipment. These two data sets were matched together to give the complete vertical profile along the road.\(^\text{11}\)

The levelling was done in one direction. For the other direction the gradient profile was mirrored.

### 5.4 The test route

The test route, see Appendix D, is situated in the community of Linköping, outside the urban area in an open landscape, see figure 5.5.

![The test route in Linghem outside Linköping.](image)

**Figure 5.5 The test route in Linghem outside Linköping.**

General description of the test route:

- length: 800 m
- both directions used

\(^{11}\) All road data have been measured in another VTI project.
• gradient (direction 1):\textsuperscript{12}
  - min: -1.0 (\%)
  - max: 1.2 (\%)
  - mean: 0.21 (\%)

• average roughness both directions for the total data set: 1.2 (mm/m) (min: 0.65; max: 3.0)

• average macro texture both directions for the total data set: 0.81 (mm) (min: 0.52; max: 1.0)

• average crossfall:
  - average direction 1: -3.1 (\%)
  - average direction 2: -3.8 (\%).

The road surface conditions on the test route are judged to be approximately representative for Swedish main roads.

5.5 Measurement procedure for coastdown

There have been measurements for three different vehicle modes, see table 5.3.

Table 5.3 Measurement modes and dates.

<table>
<thead>
<tr>
<th>The vehicle</th>
<th>Unloaded</th>
<th>Loaded</th>
</tr>
</thead>
<tbody>
<tr>
<td>Truck without trailer</td>
<td>14/10</td>
<td>-</td>
</tr>
<tr>
<td>Truck with trailer</td>
<td>14/10; 21/10</td>
<td>21/10</td>
</tr>
</tbody>
</table>

There have been coastdowns from different initial speeds repeated three times each per mode (table 5.3) and road direction: 80; 50; 80; 50; 80; 50 km/h

Instructions for measurements:

• Start with a full fuel tank per day if possible
• The road surface shall be dry
• Average wind speed < 1 m/s if possible
• Adjust tyre pressure to 7.5 bar on the driving axle and to 9 bar at other axles after conditioning until a stabilized temperature is reached
• Check tyre pressure, tyre temperature in parallel, at least twice a day for warmed up tyres
• Measure and document tyre temperature at least before and after each series of coastdowns
• Measure the vehicle weight and note the odometer reading
• Side position: take a position in the centre of the wheel tracks
• Accelerate to initial speed and put the clutch into neutral position before entering the start position of the test route
• Begin the data collection before passing the start marking

\textsuperscript{12} Direction 1: towards Linköping.
• If traffic is supposed to influence air resistance push the button marking not useful data
• End the data collection after passing the end marking of the test route
• At the end of a measuring day fill the fuel tank up and make a note of the odometer reading and the amount of fuel filled.

Special measurements like vehicle weight, tyre pressure etc. shall always have odometer reading in parallel.

To measure tyre pressure without changing the tyre pressure by leakage is not an easy task. The large number of tyres, 16 in total for the truck and trailer, contributes to the problem. The tyre pressure measurements have been performed by a tyre company in Linköping\(^\text{13}\). The same measuring unit was used for all tyre pressure measurements.

### 5.6 Meteorological conditions

The conditions are described by using a weather station (21/10) placed approximately 10 m away from the road and 200 m away from the west endpoint of the test road, see figure 5.3.

For measurements 14/10 observations from nearby meteorological stations were used and adjusted to conditions representing the use of the described weather station.

Wind speed and direction was registered on a height of 1.5 m.

In Appendix E meteorological conditions for each coastdown are presented.

The road surface conditions were not perfect at 21/10 since the surface was wet during the first part with loaded vehicle. The wet surface was caused by fog, i.e. not from rain. During the second part of the measurements the same day the surface was partly dry.

### 5.7 Measured data

In Appendix E information per coastdown is documented including some important information like:

- coastdown number
- date
- speed at the start and at the end of each coastdown
- average \(dv/dt\)
- ambient temperature
- meteorological wind speed
- meteorological wind direction in relation to the vehicle movement direction
- ambient air pressure
- ambient air moisture.

In Appendix E, figure E1–E8, all coastdowns are presented in diagram form.

In table 5.4 number of coastdowns at different modes are presented.

---

\(^{13}\) Däckhuset.
Table 5.4 Number of coastdowns*

<table>
<thead>
<tr>
<th></th>
<th>Unloaded</th>
<th>Loaded</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Truck without trailer</td>
<td>(14/10): 8</td>
<td>0</td>
<td>8</td>
</tr>
<tr>
<td>Truck with trailer</td>
<td>(14/10): 11</td>
<td>(21/10): 12</td>
<td>35</td>
</tr>
<tr>
<td>Total</td>
<td>31</td>
<td>12</td>
<td>43</td>
</tr>
</tbody>
</table>

*(xx/yy): date of measurements.

Per measuring mode the intention was to have 12 coastdowns: two directions; three initial speed levels and two coastdowns for each combination. The resulting numbers deviate from this intention especially for truck without trailer.

As a first approach the coastdowns have been split into 1 m long sections. The test route has a length of 800 m. Each coastdown results in 800 observations on aggregation level 1 m.

On aggregation level 25 m the number of observations is at most 32 per coastdown. Each such section, 1 m or 25 m, for each coastdown constitutes one observation in the analyse.

The data file for analyses has been reduced for observations with number of satellites:
- less than 8
- higher than 15.

The reason for excluding observations with more than 15 satellites was that such a high number is an expression for an error.

The total number of observations (25 m) with trailer:
- without load, 686
- with load, 361
- total, 1047.

The total number of observations (25 m) without trailer: 243.

Problems compared to intentions:
- no tyre adjustments 14/10
- considerable higher wind speed than should be accepted 14/10
- moist road surface 21/10
- not possible, for practical reasons, to measure tyre pressure for loaded and unloaded vehicle for the same conditions (21/10).

Since tyre pressure has not been adjusted in a desired way it is important to judge or estimate the variation in tyre pressure during measurements. If there is no leakage the tyre pressure should vary with the tyre temperature and the air pressure. There could also be an effect of tyre load at stand still.

If the air pressure would change by $+dP$ the tyre overpressure should change by $-dP$. 
For a constant tyre volume:

\[
\frac{(P_{w0} + P_{air0})}{1000}/(T_{w0} + 273) = \frac{(P_{w1} + P_{air1})}{1000}/(T_{w1} + 273)
\]

- \(P_{w0}\): tyre overpressure at occasion 0 (mbar)
- \(P_{w1}\): tyre overpressure at occasion 1 (mbar)
- \(P_{air0}\): air pressure at occasion 0 (mbar)
- \(P_{air1}\): air pressure at occasion 1 (mbar)
- \(T_{w0}\): tyre temperature at occasion 0 (°C)
- \(T_{w1}\): tyre temperature at occasion 1 (°C).

This formula has been used in order to estimate tyre pressure at different occasions.

There were no tyre pressure adjustments between 14/10 and 21/10. The tyre pressure 14/10 could be estimated based on the pressure 21/10 and on tyre temperature and air pressure both days. The estimated pressure 14/10 is then 2% below the desired values in average (7.5 and 9.0 respectively).

One question of interest is if tyre pressure changes as a function of tyre load for a tyre at constant temperature and air pressure at stand still. This is of importance in order to judge if there has been a leakage.

For practical reasons, in this project, tyre pressure could not be measured at the location where the load was changed. Because of this there will be different conditions for tyre pressure measurements with and without load. If the tyre pressures measured with load are adjusted for changes in tyre temperature and air pressure for conditions equal to those without load, the estimated tyre pressure is below the pressure without load. The difference between measured and estimated values is small, approximately 2%. The hypothesis was that the tyre pressure would be equal or decrease when the load decreased.

The ambient temperature at measurements without load 21/10 has been approximately 1.5 °C higher compared to measurements with load. The tyre temperature 21/10 without load has been 0.4 °C higher than with load. This difference in tyre temperature is caused both by the difference in ambient temperature and in load. The load is estimated to increase the tyre temperature with 1.1 °C.

One hypothesis could be that the driving axle tyres would have a higher temperature compared to the other axle tyres on the truck. In Appendix E it can be seen that this is not the case.

When looking at tyre temperatures for different axles the load per tyre could be of interest, see table 5.5.
Table 5.5 Tyre loads.*

<table>
<thead>
<tr>
<th>Axle</th>
<th>Tyres/axle</th>
<th>Unloaded (N)</th>
<th>Loaded (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Truck</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>27125</td>
<td>35432</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>9712</td>
<td>20037</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>19424</td>
<td>40074</td>
</tr>
<tr>
<td>Trailer</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>12655</td>
<td>24550</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>12655</td>
<td>24550</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>12949</td>
<td>26242</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>12949</td>
<td>26242</td>
</tr>
</tbody>
</table>

*Values at the occasions for weight measurements 14/10 (unloaded) and 21/10 (loaded). The distribution between the second and third axle on the truck is based on the assumption that the total load per axle in the boogie is equal. Unloaded is measured 14/10 only. For the trailer the first two axles and the last two axles respectively are weighted together. The axle weight distribution in the front and in the rear of the trailer is based on the assumption of equal distribution.

A data set for the analysis has been prepared. This data set includes observed data for the different variables of interest. In the basic data set each coastdown has been split into observed values per meter. From this 1 meter level aggregation is possible to do for example to 25 m. The 1 m level is an aggregation of the measured data at 100 Hz.

In order to develop driving resistance functions it is of importance to have high correlations between the dependent and the explanation variables and in parallel not to have high correlations between explanation variables. In Appendix F correlation analysis is presented for two data sets, 25 m aggregation level only, restricted to measurements with trailer:

- full data set
- reduced data set (see below).

Both data sets include the same variables.

The correlation includes variables: \( \frac{dv}{dt} \); \( v \); \( T \); \( vl \); \( Pair \); \( fxl \); \( dns \); \( moist \); \( gr \); \( iri \); \( mpd \); \( crf \) and \( macc \).

In total there are 66 correlation values between different variables other than \( \frac{dv}{dt} \). The number of absolute correlation values in different size classes with exception for \( \frac{dv}{dt} \) in the total data set:

- above 0.4: 13
- above 0.5: 10
- above 0.6: 9
- above 0.7: 8.
The limit value 0.4 has been subjectively chosen.

The variables with absolute correlation values above 0.4 with exception for \( dv/dt \) combinations in the total data set:

- \( fxl-v \): 0.95
- \( gr-v \): 0.42
- \( dns-temp \): -0.68
- \( macc-T \): 0.86
- \( Pair-vl \): 0.97
- \( dns-vl \): 0.84
- \( moist-vl \): 0.95
- \( dns-Pair \): 0.89
- \( moist-Pair \): 0.97
- \( moist-dns \): -0.77
- \( macc-moist \): 0.51
- \( mpd-gr \): 0.43
- \( crf-gr \): 0.42

These correlations should be of special interest if the pair of variables is included in different explanatory variables in the analysis. In the road surface analysis there are some variables with a potential to cause problems. If a pair of variables with high correlation is included in the same explanatory variable there should not be any problem.

Because of the correlation between gradient and \( mpd \), the basic data set has been adjusted:

- observations with low gradient (downhill) and low \( mpd \)
- observations with high gradient (uphill) and high \( mpd \).

After reduction for \( gr-mpd \) correlation:

- number of observations without load, 550
- number of observations with load, 287
- number of observations in total, 837
- correlation \( gr-mpd \): 0.132
- correlation \( gr-v \): -0.368
- correlation \( crf-gr \): -0.617.

For an analysis including gradient and \( mpd \) as independent variables the data reduction is necessary. For analysis not including \( mpd \) the basic data set should be used. The correlations after reduction of the data set are presented in table F4. In table F2 min and max and averages for different variables in the reduced data set are presented.

In Appendix E coastdown speed curves are presented, speed versus distance. One quality control of constant conditions from measurement to measurement is if the curves with the same start speed are parallel. In many cases, but not in all, they are parallel. If not parallel the reason should be possible to explain for example by different wind speed conditions. Coastdowns with different initial speeds should not be parallel because \( dv/dt \) is a function of \( v \).
5.8 Examples of driving resistance parameter values from the literature

Transmission losses

The churning losses have been estimated by functions documented in (Carlsson et al., 2008):

\[ P_{vx} = 5.1 \times \left( \frac{Prat}{220000} \right) \times nr^{1.62} \]
\[ P_{bx} = 10.08 \times \left( \frac{Prat}{1000} \right)^{0.42} \times nrk \]

\( P_{vx} \): gear box churning losses (W)
\( P_{bx} \): differential churning losses (W)
\( Prat \): engine max power (W)
\( nr \): engine speed (rps)
\( nrk \): rotation speed of the differential incoming axle (rps)

These functions are based on information from truck manufacturers.
For parameter values representing the coastdown truck one could expect transmission losses as presented in table 5.6.\textsuperscript{14}

\textsuperscript{14} Data based on contacts with truck manufacturers.
Table 5.6 Transmission churning losses for vehicle parameters representing the coastdown truck based on (Carlsson et al., 2008).

<table>
<thead>
<tr>
<th>Unit</th>
<th>Vehicle speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Notation 10 15 20 25</td>
</tr>
<tr>
<td>Differential</td>
<td>Pbx..(W) 619 1194 1902 2731</td>
</tr>
<tr>
<td></td>
<td>Pbx/v..(N) 62 80 95 109</td>
</tr>
<tr>
<td>Gear box</td>
<td>Pvx..(W) 1649 2473 3297 4121</td>
</tr>
<tr>
<td></td>
<td>Pvx/v..(N) 165 165 165 165</td>
</tr>
<tr>
<td>Total</td>
<td>(Pbx+Pvx)/v (N) 227 245 260 274</td>
</tr>
</tbody>
</table>

*Direct gear position. During coastdown the gear has been in neutral position.

In (Rexeis, 2005) the sum of churning losses and mechanical losses are expressed in one function. There are separate functions for the differential (final gearbox) and the gearbox:

\[ P_{\text{diff}} = P_{\text{rated}} \times 0.0025 \times (-0.47 + 8.34 \times \frac{n_{\text{wheel}}}{n_{\text{rat}}} + 9.53 \times \text{ABS}(P_{\text{dr}}/P_{\text{rat}})) \]

- \( P_{\text{diff}} \): total power losses in the differential (final gearbox) (W)
- \( P_{\text{rated}} \): max engine power (W)
- \( P_{\text{dr}} \): power to overcome driving resistance (without transmission losses) (W)
- \( n_{\text{wheel}} \): rotational speed of the wheels (rpm)

\[ P_{16,\text{gear}} = P_{\text{rat}} \times 0.0025 \times (-0.66+4.07*(n_r*60/(n_{\text{rat}}*I_{16}))+0.000867*\text{abs}(P_{\text{dr}}+P_{\text{diff}}/P_{\text{rat}})) \]

- \( P_{16,\text{gear}} \): gearbox losses when the 16th gear is used
- \( n_r \): engine speed (rps)
- \( n_{\text{rat}} \): engine speed at \( P_{\text{rat}} \) (rpm)
- \( I_{16} \): the gear ratio in gear position 16.

In order to estimate just churning losses with these functions \( P_{\text{dr}} \) and \( P_{\text{diff}} \) are assigned the zero value.

The churning losses for the coastdown truck have been estimated in table 5.7.
Table 5.7 Transmission churning losses for the coastdown truck based on (Rexeis, 2005).

<table>
<thead>
<tr>
<th>Unit</th>
<th>Vehicle speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Notation 10 15 20 25</td>
</tr>
<tr>
<td>Differential</td>
<td>Pdiff (W)</td>
</tr>
<tr>
<td></td>
<td>Pdiff/v (N)</td>
</tr>
<tr>
<td>Gear box</td>
<td>P_{16, gear}/v (W)</td>
</tr>
<tr>
<td></td>
<td>P_{16, gear} (N)</td>
</tr>
<tr>
<td>Total</td>
<td>(Pdiff+P_{16, gear}/v) (N)</td>
</tr>
</tbody>
</table>

**Bearing resistance**

In (Mitschke, 1982) we have:

\[ F_b = C_b \cdot F_z \]

\[ C_b = 0.0005. \]

**Rolling resistance**

In (Sandberg, 2008) rolling resistance values for trucks are reported:

- 215/70R22.5:
  - steered-wheel tyres: 0.0057–0.0063
  - drive-wheel tyres: 0.006–0.007

- 315/80R22.5:
  - steered-wheel tyres: 0.0045–0.0055
  - drive-wheel tyres: 0.0057–0.007

These values have been measured according to ISO 9948.\(^{15}\)

In (Siltanen, 2010) measured rolling resistance values on a drum are presented, see table 5.8.

\(^{15}\) Drum diameter: 1.7–3.0 m; test speed: 80 or 60 km/h; warm up: speed, 80 km/h and time: 90 or 30 minutes.
Table 5.8 Rolling resistance values from drum measurements including recalculation to a flat surface for new tyres (Siltanen, 2010).

<table>
<thead>
<tr>
<th>Type of tyre</th>
<th>315/80R22.5***</th>
<th>385/65R22.5****</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>min</td>
<td>max</td>
</tr>
<tr>
<td>On a 2m drum (measured on a 3.5 m drum and recalculated to 2.0 m)*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>all season</td>
<td>steer</td>
<td>0.006</td>
</tr>
<tr>
<td>traction</td>
<td></td>
<td>0.0065</td>
</tr>
<tr>
<td>steer</td>
<td></td>
<td>0.0065</td>
</tr>
<tr>
<td>traction</td>
<td></td>
<td>0.0065</td>
</tr>
<tr>
<td>winter</td>
<td></td>
<td>0.0065</td>
</tr>
<tr>
<td>Recalculated to flat surface**</td>
<td></td>
<td></td>
</tr>
<tr>
<td>all season</td>
<td>steer</td>
<td>0.0045</td>
</tr>
<tr>
<td>traction</td>
<td></td>
<td>0.0048</td>
</tr>
<tr>
<td>steer</td>
<td></td>
<td>0.0048</td>
</tr>
<tr>
<td>traction</td>
<td></td>
<td>0.0048</td>
</tr>
</tbody>
</table>

*ISO 28580; **Recalculation based on (Mitschke, 1982)
16; ***8.25–8.5 bar depending on load index; ****8.5–9.0 bar depending on load index.

Approximately 30% of the rolling resistance for a new tyre is caused by the tread. The rolling resistance for worn out tyres is then estimated to be 30% lower compared to table 5.6.

In (Reithmaier et al., 2000) rolling resistance values measured on a drum are presented. Description of the measurements:
- ISO 9948
- drum diameter: 1707 mm
- conditioned at least 6 h under test room conditions
- tyres are run under test conditions for 120 minutes at 80 km/h before measurements

---

16 Function for estimation of rolling resistance on a flat surface based on measurements on a drum (Mitschke, 1982):

\[ F_{RT}/F_{RE} = (1 + (2 \times rwh)/D)^{0.5} \]

where
- \( D \) is the diameter of the drum (m)
- \( F_{RT} \) is the rolling resistance on a drum (N)
- \( F_{RE} \) is the rolling resistance on a flat surface (N)
- \( 2 \times rwh \) is the diameter of the tyre
- the tyre pressure is adjusted on the conditioned tyre, during measurement tyre pressure can build up freely
- test room temperature: 25 °C
- the rolling resistance is calculated by using a formula in ISO 9948
- two tyres are measured from each manufacturer and dimension.

Table 5.9 Rolling resistance values* from drum measurements (Cr0D) including recalculation to a flat surface (Cr0) for new tyres (Reithmaier et al, 2000).

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Used for</th>
<th>Load (kg)</th>
<th>Pressure (bar)</th>
<th>Cr0D min</th>
<th>Cr0D max</th>
<th>Cr0D mean</th>
<th>Cr0D min</th>
<th>Cr0D max</th>
<th>Cr0D mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>275/70 R22.5</td>
<td>steering-axle</td>
<td>2730</td>
<td>9.0</td>
<td>0.005</td>
<td>0.006</td>
<td>0.006</td>
<td>0.004</td>
<td>0.005</td>
<td>0.005</td>
</tr>
<tr>
<td>275/70 R22.5</td>
<td>drive-axle</td>
<td>2730</td>
<td>9.0</td>
<td>0.006</td>
<td>0.007</td>
<td>0.006</td>
<td>0.004</td>
<td>0.005</td>
<td>0.005</td>
</tr>
<tr>
<td>315/80 R22.5</td>
<td>steering-axle</td>
<td>3466</td>
<td>8.5</td>
<td>0.004</td>
<td>0.005</td>
<td>0.004</td>
<td>0.003</td>
<td>0.004</td>
<td>0.003</td>
</tr>
<tr>
<td>315/80 R22.5</td>
<td>drive-axle</td>
<td>3466</td>
<td>8.5</td>
<td>0.005</td>
<td>0.007</td>
<td>0.006</td>
<td>0.004</td>
<td>0.005</td>
<td>0.004</td>
</tr>
</tbody>
</table>

* ISO 9948; **Estimated based on (Mitschke, 1982).

To summarize one can notice more than minor difference in Cr0 between different literature sources (dimension 315/80R22.5). Drive axle Cr0D is always at least as high as the steering axle.

There is information in the literature about Cr being a function of the vertical load $F_z$ (Rexeis et al., 2005):\(^17\)

\[
Cr = Crz0 - Crz1 \times F_z/1000
\]

$Crz0 = 0.00825$

$Crz1 = 0.000075$

where

$F_z$: vertical load (N)

$Crz0$ and $Crz1$ are constant parameters.

This means that the rolling resistance ($Fr$) depends quadratic on $F_z$.

Based on this function rolling resistance ($Cr$) has been estimated for different segments of HGV, see table 5.10.

\(^{17}\) Refering to (Evêquez, 1995)
Table 5.10  Rolling resistance coefficient (Cr) for different HGV segments (Euro 3) (Rexeis et al., 2005).*

<table>
<thead>
<tr>
<th>GVW (t)</th>
<th>Load factor</th>
<th>0%</th>
<th>50%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rigid truck</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>26–28</td>
<td>0.00735</td>
<td>0.00681</td>
<td>0.00626</td>
<td></td>
</tr>
<tr>
<td>28–32</td>
<td>0.00742</td>
<td>0.00685</td>
<td>0.00629</td>
<td></td>
</tr>
<tr>
<td>32–</td>
<td>0.00737</td>
<td>0.00672</td>
<td>0.00607</td>
<td></td>
</tr>
<tr>
<td>Truck with trailer</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>34–40</td>
<td>0.00732</td>
<td>0.00657</td>
<td>0.00581</td>
<td></td>
</tr>
<tr>
<td>40–50</td>
<td>0.00751</td>
<td>0.00680</td>
<td>0.00609</td>
<td></td>
</tr>
<tr>
<td>50–60</td>
<td>0.00754</td>
<td>0.00679</td>
<td>0.00604</td>
<td></td>
</tr>
</tbody>
</table>

*These values are used as representative for average road conditions.

One can notice that Cr has a maximum for rigid truck 28–32 t and for truck with trailer 40–50 t. These values are used to represent average road conditions i.e. effects of iri and mpd should be included.

In (Hammarström et al., 2008) the influence of the road surface on driving resistance has been analysed. The study covered three vehicle types including one heavy truck. For the heavy truck a significant iri effect has been proved:18

\[ F_{r,iri} = 0.00170 \times \text{iri} \times 9.81 \times m \]

\( F_{r,iri} \): additional driving resistance caused by road roughness (N)

The estimated mpd effect for the truck had what is judged a wrong sign but it still proved different from zero:

\[ F_{r,mpd} = -0.00151 \times \text{mpd} \times 9.81 \times m \] (N)

In a standardized method for rolling resistance measurements (ISO, 2009) an adjustment function for ambient temperature is included:

\[ Cr_{25} = Cr_0 \times (1 + K \times (\text{tamb} - 25)) \]

\( Cr_{25} \): basic rolling resistance at an ambient temperature of 25° C

\( K \): parameter value:

- 0.010 for load indices <121 (=1450 kg)
- 0.006 for load indices ≥121 (=1450 kg)

---

18 GVW: 17.7 t; tyre: 12.00R20 and 445/65R22.5.
**Air resistance coefficient**

In a literature survey, see *(Hammarström, 1999)* typical air resistance coefficients \(Cd_0\) for different vehicle bodies of year model around 1980 are presented (no wind deflectors):

- truck with trailer with box vehicle body: 0.73–0.86 and median 0.78
- truck with box vehicle body: 0.59–0.79 and median 0.62

Wind deflectors have been estimated to give reductions:

- truck: 13%
- truck with trailer: 14%

Year models including wind deflector around 1980 are then expected to have \(Cd_0\) values:

- truck with trailer with box vehicle body: 0.63–0.74 and median 0.67
- truck with box vehicle body: 0.51–0.69 and median 0.54.

With the same type of vehicle body different vehicle combinations are estimated to have \(Cd_0\) values in the following increasing order:

- truck
- truck with semitrailer
- truck with trailer.

For the same type of vehicle combination different vehicle bodies are estimated to have \(Cd_0\) values in the following increasing order:

- box or tanker
- timber loaded
- flat sided
- tipper

For the estimations of emission factors in HBEFA typical \(Cd\) values have been estimated per GVW class, see table 5.11 *(Rexeis et al., 2005)*. These values are used for estimation of total air resistance, i.e. they should represent \(Cdt\).
Table 5.11  Total air resistance coefficients (Cdt) and frontal area (Ayz) for different HGV segments (Euro 3) (Rexeis et al., 2005).

<table>
<thead>
<tr>
<th>GVW(t)</th>
<th>Cdt</th>
<th>Ayz (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rigid truck</td>
<td></td>
<td></td>
</tr>
<tr>
<td>26–28</td>
<td>0.64</td>
<td>7.5</td>
</tr>
<tr>
<td>28–32</td>
<td>0.66</td>
<td>7.9</td>
</tr>
<tr>
<td>32–</td>
<td>0.66</td>
<td>8.0</td>
</tr>
<tr>
<td>Truck with trailer or semitrailer (AT or TT)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>34–40</td>
<td>0.50</td>
<td>9.0</td>
</tr>
<tr>
<td>40–50</td>
<td>0.52</td>
<td>9.0</td>
</tr>
<tr>
<td>50–60</td>
<td>0.63</td>
<td>8.1</td>
</tr>
</tbody>
</table>

The same Cdt is used for truck with trailer and truck with semitrailer in the same GVW interval.

The values in table 5.11 do not explicitly include the influence of HGV distribution on vehicle bodies, but they are used as representative values for the whole group of HGV per segment. The main objective has been that \( Cd(>40t)>Cd(<40t) \).

In order to describe the change in \( Cd \) by year model correction factors have been used:

- Euro0, 1.08
- Euro1, 1.042
- Euro2, 1.026
- Euro3, 1
- Euro4, 0.99
- Euro5, 0.98.

5.9  Analysis

The analysis of measured data includes:
- different function approaches, see section 3 and Appendix G
- alternative ways to include data in the analysis
- different data sets: with or without trailer; total or reduced
- different aggregation levels (1 m and 25 m respectively).

There is no exact function form available for all types of driving resistance. The only forms not questioned are \( F_{acc} \) and \( F_{gr} \).

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19 M. Rexeis in e-mail 2010.
There are alternatives for the inclusion of the gradient:
- An average gradient between the first axle on the truck and the last axle on the trailer
- Separate gradients for the truck ($gr1$), between the first and the third axle on the truck, and for the trailer ($gr2$), between the first and the last axle on the trailer.

Road surface effects influence the tyres. One alternative is to define observations with road surface measures tyre by tyre. Instead, an alternative is used corresponding to the gradient with average road surface measures between the first and last axle on the truck and on the trailer respectively:
- The truck (6 m interval (=1st to last axle)):
  - $mpd1$: macrotexture for the truck
  - $iri1$: roughness for the truck
  - $crf1$: crossfall for the truck
- The trailer (10 m interval (=1st to last axle)):
  - $mpd2$: macrotexture for the trailer
  - $iri2$: roughness for the trailer
  - $Crf2$: crossfall for the trailer

This adjustment of the analysis file is based on the 1 m interval file.

The expression of $F_i$ includes several questions:
- influence of vertical load?
- influence of temperature?
- influence of tyre pressure?
- influence of road surface conditions?
- influence of speed?
- influence of different tyre types, dimensions and models (for example: speed index, load index and manufacturer)?
- influence of tread wear etc.?

In most cases it is not a question whether there is an effect; instead the question concerns the size, the interactions and the function form for influence.

There are different types of tyres on the truck and on the trailer of the test vehicle; super single on the trailer and standard tyres on the truck. One could then expect different $Cr$ on the truck and on the trailer. Other conditions of importance are differences between the spring systems on the truck and the trailer.

The risk for systematic differences between 14/10 and 21/10, tyre pressure and registration of meteorological conditions, motivate a split of data into 14/10 and 21/10. The conditions especially concerning meteorological conditions were more suitable for traditional coastdowns 21/10. However, the wind speed range for both days could be an advantage when trying to estimate a parameter value ($Cd1$) for resulting wind not being parallel to the driving direction.
There is a hypothesis for the rolling resistance per tyre being a function of the squared normal force:\textsuperscript{20}

\[
F_{r0} = F_z \cdot Crz0 + F_z^2 \cdot Crz1
\]

This expression makes it necessary to describe \( F_z(i,j) \) per tyre. The results could be expected to depend on the load distribution on different tyres:

\[
F_{r0}(i,j) = F_z(i,j) \cdot Crz0 + F_z(i,j)^2 \cdot Crz1
\]

\( F_z(i,j) \): vertical load per wheel on axle \( j \) on vehicle \( i \).

Two alternatives have been used for load distribution:

- one with estimated load per axle and tyre
- one with a simplified approach: the same load for all tyres per vehicle.

Different tyres on the test vehicle have different accepted max load (\( F_{zmx} \)).

Rolling resistance per tyre:

\[
F_r = F_z(i,j) \cdot (Crz0 + Crz1 \cdot rF_z(i,j)) \quad \text{where} \quad rF_z(i,j) = F_z(i,j) / F_{zmx}(i,j)
\]

By the variation in the vehicle mass there should be a possibility to estimate the resistance caused by the transmission. The estimation of \( F_{trm} \) in functions with all parameters significantly different from 0 has been used as a “true” input value in some other parameter estimations.

The basic function used for parameter estimation:

\[
\frac{dv}{dt} = -(trm + m1 \cdot 9.81 \cdot \sin(gr1) + m2 \cdot 9.81 \cdot \sin(gr2) + Cr \cdot 9.81 \cdot (m1 + m2) + 
+ Cd0 \cdot (1 + Cd1 \cdot \sin(b)) \cdot fxl)/macc
\]

\[
fxl = dns \cdot Ayz \cdot \cos(b) \cdot vlr^2 / 2
\]

\( fxl \): a help variable introduced of practical reasons in the regression analysis.

The literature includes information about an influence of the aggregation level on estimated parameter values. Two interval aggregation levels have been analysed: 1 m and 25 m. The purpose with testing different aggregation levels is to check if the results are sensitive for these alternatives.

For the estimation of parameter values \textbf{SPSS Nonlinear Regression Analysis} has been used.

The main purpose with this study is to add new data for PHEM simulations in order to make emission factors in HBEFA more representative. To fulfil this objective in a scientific way is not easy because of:

- just one new study compared to literature, how to weight
- different studies represent different conditions, how to compare.

\textsuperscript{20} Based on (Rexeis, 2005).
In a first step estimated parameters from this study are compared with literature data for box vehicle body. The parameter values used in PHEM should represent an average for all vehicle bodies, for all road surface conditions and for all meteorological conditions. Most rough such estimations have been performed for two alternatives: coastdown and literature. More detailed descriptions of the method used are presented in section 7.
6 Results of measurements

Many different conditions influence driving resistance. In order to make the results useful in general different model approaches including these influencing variables were formulated and tested.

In Appendix G tested functions judged being of major interest including estimated parameters are presented.

There are results presented for two vehicle segments: truck with trailer 50–60 t and rigid truck 26–28 t. The same truck is used both in the vehicle combination and as rigid truck.

The analysis is based on data from 14/10 and 21/10 (2009) including with and without trailer. Measurements with a trailer include both loaded and unloaded drives. Without a trailer there are only measurements without load.

If results are based on a reduced data set, because of high correlation between explanatory variables, this is stated, see section 5.7.

Data is on two interval aggregation levels: 1 m and 25 m. The presented results are based on 25 m if nothing else is stated.

6.1 Truck with trailer

Function 5.1 represents the basic function in the analysis. In order to analyse the influence of other variables than included in function 5.1 different extensions of 5.1 have been made.

In table 6.1 estimated parameter values in the driving resistance basic function for a truck with trailer are presented.

<table>
<thead>
<tr>
<th></th>
<th>(\text{trm})</th>
<th>(\text{Cr})</th>
<th>(\text{Cd0})</th>
<th>(\text{Cd1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>258</td>
<td>0.00528</td>
<td>0.832</td>
<td>1.73</td>
</tr>
<tr>
<td>Min**</td>
<td>13.5</td>
<td>.00448</td>
<td>0.772</td>
<td>1.41</td>
</tr>
<tr>
<td>Max**</td>
<td>503</td>
<td>.00608</td>
<td>0.893</td>
<td>2.06</td>
</tr>
</tbody>
</table>

\(\text{dv/dt} = -(\text{trm} + m1 \cdot 9.81 \cdot \text{gr1} + m2 \cdot 9.81 \cdot \sin(\text{gr2}) + (m1 + m2) \cdot 9.81 \cdot \text{Cr} + \text{Cd0} \cdot (1 + \text{Cd1} \cdot \sin(\theta)) \cdot \text{fsl}) / \text{macc}\).

Especially the \(\text{Cd0}\) value, limit values +/-7%, is estimated with high accuracy. \(\text{Cr}\) (+/-15%) and \(\text{Cd1}\) (+/-18%) are estimated with at least acceptable accuracy. The \(\text{trm}\) (+/- 95%) estimation has an interval of uncertainty which can not be described as acceptable.

The conditions for coastdown measurements were expected to be better for 21/10 compared to 14/10 because of less wind speed. Parameter estimation based on 21/10 data are presented in table G3a. The \(\text{trm}\) value was not proved different from zero based on 21/10 data. Even if judged better conditions at 21/10, max wind speed 2.7 m/s compared to 5.4 m/s at 14/10, the results based on just 21/10 data compared to the total
data set do not express such a difference. One explanation could be that the number of observations is reduced when just including 21/10 data in the analysis. Another explanation could be a more narrow meteorological wind speed range reducing the possibility to estimate the $CdI$ value. In table G3a estimated parameter values for 14/10 are presented as well.

With an **aggregation level of 1 m** the confidence intervals of the estimated parameters are wider compared to the 25 m interval. The $trm$ estimation has not been proved to be different from zero at the 1 m level with function 5.1.

**Transmission losses** ($trm$) with the gear in neutral position are estimated to 258 N. The confidence interval for $trm$ has a wide range but do not include zero.

At a vehicle speed of 20 m/s and average meteorological wind speed conditions the estimated transmission churning losses constitute between 4.2 and 6.1% of the total driving force ($Fx$) depending on the load factor, see table 6.3. These proportions decrease with increasing vehicle speed.

At coastdown there is a small power passing through the final gear box equal to the churning losses in the gear box. There is no power passing through the gear box at coastdown. This power passing through the final gear box will cause some mechanical transmission losses included in $trm$. The estimated $trm$ substantially constitutes churning losses.

The **air resistance** is a function of:
- vehicle speed ($v$)
- meteorological wind speed ($vl$)
- the angle ($a$) between the driving direction and meteorological wind.

The $Cd$ value is expressed as a function of the angle ($b$) between the driving direction and the direction of the resulting wind. The $b$-angle is a function of the vehicle speed, the speed of the meteorological wind and the $a$-angle. Some examples on the $b$-angle for different conditions are presented in table H2 and H3.

Based on estimated parameters in table 6.1 some examples on $Fair$ have been calculated, see figure 6.1 and 6.2.
Figure 6.1 Air resistance (Fair) as a function of the angle (a) between meteorological wind and the x-axle of the vehicle at different vehicle speeds. Meteorological wind speed=5 m/s.

Figure 6.2 Air resistance (Fair) as a function of the angle (b) between resulting wind and the x-axle of the vehicle at different vehicle speeds. Meteorological wind speed=5 m/s.

If the angle (a) between the driving direction and the meteorological wind direction is uniformly distributed around the horizon the average air resistance will change with the speed of the vehicle and the meteorological wind speed, see table 6.2a.
Table 6.2a  The average total change (%) of air resistance with increasing meteorological wind speed at different vehicle speeds. The angle \((a)\) between the speed wind and meteorological wind is assumed to be uniformly distributed around the horizon.*

<table>
<thead>
<tr>
<th>Met. wind speed (m/s)</th>
<th>Vehicle speed (m/s)</th>
<th>5.0</th>
<th>10.0</th>
<th>15.0</th>
<th>20.0</th>
<th>25.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>86</td>
<td>37</td>
<td>23</td>
<td>17</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>215</td>
<td>86</td>
<td>52</td>
<td>37</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>356</td>
<td>147</td>
<td>86</td>
<td>60</td>
<td>46</td>
<td></td>
</tr>
</tbody>
</table>

*Both a change in \(C_d\) and in resulting wind speed projection; Estimated as \(100\times(Fair(\text{including met. w.})/Fair(\text{vl}=0) - 1)\) per vehicle speed; Average of 8 values.

The effects in table 6.2a include both a change in \(C_d\) and in resulting wind speed. In table 6.2b the effect of just the resulting wind speed is presented.

Table 6.2b  The general average change (%) of air resistance, at constant \(C_d\), with increasing meteorological wind speed at different vehicle speeds. The angle \((a)\) between the speed wind and meteorological wind is assumed to be uniformly distributed around the horizon.*

<table>
<thead>
<tr>
<th>Met. wind speed (m/s)</th>
<th>Vehicle speed (m/s)</th>
<th>5.0</th>
<th>10.0</th>
<th>15.0</th>
<th>20.0</th>
<th>25.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>24.4</td>
<td>5.7</td>
<td>2.3</td>
<td>1.2</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>92.6</td>
<td>24.4</td>
<td>10.5</td>
<td>5.7</td>
<td>3.5</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>174.2</td>
<td>54.6</td>
<td>24.4</td>
<td>13.5</td>
<td>8.4</td>
<td></td>
</tr>
</tbody>
</table>

*As a change in resulting wind speed size and projection; Estimated as \(100\times(Fair(\text{including met. w.})/Fair(\text{vl}=0) - 1)\) per vehicle speed. This table is valid for all road vehicles; Average of 8 values.

In table 6.2c the influence of meteorological wind on the \(Fair\) speed dependency is demonstrated.
Table 6.2c  The air resistance vehicle speed dependency at increasing meteorological wind speed. The angle (a) between the speed wind and meteorological wind is assumed to be uniformly distributed around the horizon.*

<table>
<thead>
<tr>
<th>Met. wind speed (m/s)</th>
<th>Vehicle speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5.0</td>
</tr>
<tr>
<td>0</td>
<td>0.06</td>
</tr>
<tr>
<td>3</td>
<td>0.10</td>
</tr>
<tr>
<td>6</td>
<td>0.14</td>
</tr>
<tr>
<td>9</td>
<td>0.18</td>
</tr>
</tbody>
</table>

*As a change in resulting wind speed projection; Estimated as (Fair(v)/Fair(v=20) per wind speed; Average of 8 values.

Comments to figure 6.1 and 6.2 and table 6.2a, 6.2b and 6.2c:
- The air resistance has a maximum for $a = 0.7$ rad
- At $a>1.4$ rad (and $<3.14$) $Fair$ will be lower compared to front wind independent of vehicle speed and wind speed $(v_l)$
- At conditions judged being typical for Sweden, i.e. vehicle speed 20 m/s and wind speed 3 m/s, the air resistance will increase by 17% compared to $v_l=0$ m/s
- Just the wind effect of the meteorological total wind effect, constant Cd, constitutes a minor part of the total meteorological wind effect. The values in table 6.2b are valid for all vehicle and body types
- The speed dependency of $Fair$ decreases with increasing meteorological wind, table 6.2c
- At a speed of 20 m/s and average meteorological wind conditions the air resistance constitutes between 45 and 66% of total driving resistance depending on load factor, see table 6.3.

Increased side force will increase the driving resistance. However, the estimated effect in the data set was not significantly different from zero. There is a comparatively high correlation between $gr$ and $crf$ in measured data probably disturbing the analysis.

The rolling resistance expression has been tested including dependency of vehicle speed, normal force, ambient temperature, vehicle unit (the truck and the trailer respectively) and road surface condition.

For rolling resistance and speed dependency it was not possible to prove a parameter significantly different from zero, see function 5 in table G1b. In the reduced data set the speed parameter in $Cr$ was proved different from zero but not the speed independent parameter, see function 2 in table G2b.
The influence of the normal force on the rolling resistance parameter has been analysed with two function approaches presented in section 5. In no case has it been possible to prove such an effect with the method used, see function 6 and 7 in table G1a.

The influence of ambient temperature has been tested as a correction of rolling resistance, see function 8 in table G1a. The estimated value of the temperature parameter is significantly different from zero. The sign of the parameter, reduced rolling resistance with increased temperature, is as expected. The size of the parameter represents what is judged being an unrealistic change of $Cr$. One can notice the narrow interval of variation in measured data for ambient temperature, min 4.2 and max 5.8 °C. When $Cr$ is expressed without a temperature variable the parameters will be representative for an ambient temperature of approximately 5 °C.

A test with separate rolling resistance parameters for the truck and for the trailer resulted in no rolling resistance parameters being significantly different from zero. The estimated parameter for the truck was bigger than for the trailer, see function 4 in table G1b.

Road surface conditions and rolling resistance include roughness and macro texture. The analysis, based on the reduced data set, resulted in the following function including parameter values for rolling resistance (see table G2a and G2b):

$$Fr = (m1+m2) \times 9.81 \times (0.00375 + 0.0000916 \times iri \times v + 0.000659 \times mpd) \quad \text{(the mpd parameter is not significant different from zero (95%))}$$

One explanation for the mpd effect not being significantly different from zero could be the narrow mpd test route data interval: min 0.68 and max 0.92. The interval for iri: min 0.74 and max 2.5. Both the basic part and the iri parameters are judged as uncertain estimations.

The presented function ($Fr$) is calibrated based on the reduced data set. The estimated basic rolling resistance ($Cr0$) when compared to other data has a comparative size level.

At a speed of 20 m/s, $iri=1$ and $mpd=1$ the relative effect on $Fr$ when increasing:

- $iri$ one unit is 29%
- $mpd$ one unit is 11% (no significant effect).

The $iri$ effect increases with increasing speed. Road surface conditions at the test route has been estimated to increase $Cr$ from 0.0038 (smooth and even surface at 5 °C) to 0.0065 ($iri=1.2$ and $mpd=0.81$) for a vehicle speed of 20 m/s. Then approximately 40% of the rolling resistance at 20 m/s is caused by the road surface conditions on the test route. The $iri$ median value for Swedish national surfaced roads is between 1 and 3 depending on type of road. National roads with annual traffic above 4000 vehicles/day have $iri<1.5$.

Road surface effects based on the total data set are presented in table G1a, function 9. These results are judged being less reliable because the correlation value between gr and mpd.

---

21 $0.00375 \text{ (+/- 90%)}; 0.0000916 \text{ (+/- 43%)}$
In the road surface function above the roughness term is expressed as a linear function of $iri$, $v$ and $(m1+m2)$. We know these relations are not linear. In order to simulate the effect of road roughness on a vehicle one needs a system of differential equations, see (Hammarström and Karlsson, 1987). One function approach with a speed exponent as a function of vehicle mass has been tested, see table G2b. The resulting speed exponent, including the estimated parameter proved different from zero (95%), decreases with increasing vehicle mass.

The rolling resistance based on parameters in table 6.1 constitutes between 28 and 51%, depending on the load factor, for average wind conditions at a vehicle speed of 20 m/s.

With the reduced data set and the basic function (5.1) approach the parameter values change compared to table 6.1:

- $trm$: 293 instead of 258
- $Cr$: 0.00527 instead of 0.00528
- $Cd0$: 0.815 instead of 0.832
- $Cd1$: 1.78 instead of 1.73.

Based on the estimated parameters in table 6.1 the total driving resistance, see figure 6.3 and 6.4, have been estimated for different conditions.

![Figure 6.3 Total driving resistance (Fx) as a function of vehicle speed at different load factors (Lf=100% represents 60 tonnes vehicle weight in total). Wind speed (vl) equal to 0 m/s.](image)
Figure 6.4  *Total driving resistance (Fx) as a function of vehicle speed and meteorological wind speed (vl). (lf=50%).* The wind (vl) is supposed to be uniformly distributed around the horizon.

Comments to figure 6.3 and 6.4:

- an increase in vehicle speed from 14 to 20 m/s increases the driving resistance by 31% at vl=0 m/s and lf=50%
- an increase in lf from 0 to 50% will increase the driving resistance by 26% at 20 m/s and vl=0 m/s
- an increase in vl from 0 to 3 m/s will increase Fx by 8% at a vehicle speed of 20 m/s and lf=50%
- an increase in vl from 0 to 6 m/s will increase Fx by 18% at a vehicle speed of 20 m/s and lf=50%

Based on the function in table 6.1 the **distribution on part resistances** has been calculated, see table 6.3.
Table 6.3  Driving force distribution as a function of vehicle speed and load factor.*

<table>
<thead>
<tr>
<th></th>
<th>10 (m/s)</th>
<th>15 (m/s)</th>
<th>20 (m/s)</th>
<th>25 (m/s)**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lf=0%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ftrm</td>
<td>0.113</td>
<td>0.083</td>
<td>0.061</td>
<td>0.046</td>
</tr>
<tr>
<td>Fr</td>
<td>0.529</td>
<td>0.387</td>
<td>0.284</td>
<td>0.212</td>
</tr>
<tr>
<td>Fair</td>
<td>0.358</td>
<td>0.530</td>
<td>0.656</td>
<td>0.742</td>
</tr>
<tr>
<td>Fx</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>Lf=50%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ftrm</td>
<td>0.080</td>
<td>0.064</td>
<td>0.050</td>
<td>0.039</td>
</tr>
<tr>
<td>Fr</td>
<td>0.668</td>
<td>0.531</td>
<td>0.415</td>
<td>0.326</td>
</tr>
<tr>
<td>Fair</td>
<td>0.252</td>
<td>0.406</td>
<td>0.535</td>
<td>0.635</td>
</tr>
<tr>
<td>Fx</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>Lf=100%**</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ftrm</td>
<td>0.062</td>
<td>0.051</td>
<td>0.042</td>
<td>0.034</td>
</tr>
<tr>
<td>Fr</td>
<td>0.744</td>
<td>0.620</td>
<td>0.506</td>
<td>0.410</td>
</tr>
<tr>
<td>Fair</td>
<td>0.195</td>
<td>0.329</td>
<td>0.452</td>
<td>0.555</td>
</tr>
<tr>
<td>Fx</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
</tr>
</tbody>
</table>

*Wind speed = 3 m/s and a uniform distribution of the a-angle; **Outside the test conditions.

For increasing average wind conditions the Fair proportion will increase and the other parts decrease compared to table 6.3.

If the estimated parameters for the reduced data set are used the Fr will increase.

6.2 Rigid truck

There has been a separate analysis for the truck without a trailer. The separate terms based on the parameter estimations do not seem to be representative, see function 1 in table G3a. Anyway the sum of terms should give a representative value for the total driving resistance, at least for the actual measurement conditions. The quote between total resistance (Fx) for the rigid truck and the truck with a trailer (Lf=0%) at different vehicle speeds:

- 0.551 at 15 m/s
- 0.586 at 20 m/s
- 0.609 at 25 m/s.

The estimated parameters are based on data from the same day (14/10) both for the rigid truck and for the truck with trailer, see function 1 and 2 in table G3a, Appendix G. The presented quotes include the meteorological side wind effect (average wind speed 14/10, 5.4 m/s).

If one uses estimated values for trm and Cr in table 6.1 then Fair should be possible to isolate for the truck and for the truck with trailer based on data for 14/10.
The quote between $Fair$ (subtracting method) for the rigid truck and the truck with a trailer at different vehicle speeds:

- 0.488 at 15 m/s
- 0.562 at 20 m/s
- 0.600 at 25 m/s.

If $Fair$ is divided by:

$$Ay_z*dns*v^2/2$$

there will be a $Cdt$ estimation including all meteorological side wind effects for the conditions at 14/10. The estimated $Cdt$ values for 14/10 conditions are presented in table 6.4.

<table>
<thead>
<tr>
<th>Vehicle speed (m/s)</th>
<th>Rigid truck</th>
<th>Truck with trailer</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>0.65</td>
<td>1.30</td>
</tr>
<tr>
<td>20</td>
<td>0.69</td>
<td>1.20</td>
</tr>
<tr>
<td>25</td>
<td>0.71</td>
<td>1.15</td>
</tr>
</tbody>
</table>

*Side wind: $a=1.3$ and $a=1.8$ rad depending on driving direction. Wind speed 5.4 m/s. $Cdt$ includes all specified meteorological wind effects 14/10, see section 3.

In table G3a function 1 a $Cdt$ value 0.74 has been estimated for the rigid truck. This value represents the average speed during coastdown, approximately 15 m/s, and in parallel with a lower estimated $Cr$ compared to the one presented in table 6.1. If the true $Cr$ value should be higher compared to table G3a then the true $Cdt$ <0.74.

The $Cdt$ value in table 6.4 includes two parts:

- an aerodynamic effect expressed by $Cdo$
- an isolated wind factor (see section 4).

In table 6.5 the isolated wind factor effect for 14/10 is presented. This effect is independent of vehicle body.
Table 6.5  The isolated wind effect factor at measurements 14/10. (vl = 5.4 m/s; a=1.3 and 1.8 respectively).*

<table>
<thead>
<tr>
<th>a (rad)</th>
<th>10</th>
<th>12,5</th>
<th>15</th>
<th>17,5</th>
<th>20</th>
<th>22,5</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,8</td>
<td>0,90</td>
<td>0,90</td>
<td>0,90</td>
<td>0,91</td>
<td>0,91</td>
<td>0,92</td>
</tr>
<tr>
<td>1,3</td>
<td>1,44</td>
<td>1,33</td>
<td>1,26</td>
<td>1,22</td>
<td>1,18</td>
<td>1,16</td>
</tr>
<tr>
<td>average</td>
<td>1,17</td>
<td>1,11</td>
<td>1,08</td>
<td>1,06</td>
<td>1,05</td>
<td>1,04</td>
</tr>
</tbody>
</table>

* Isolated wind effect factor: \( \cos(b) \frac{vl r^2}{vl^2} \)

By dividing \( C_{dt} \) in table 6.4 with the values in table 6.5 per speed level there will be a rough estimation of the \( C_d \) value for the meteorological side wind conditions 14/10, see table 6.6.

Table 6.6  Air resistance coefficients (C\(d\)) for meteorological side wind conditions 14/10. (a=1.8 and 1.3 respectively; vl=5.4 m/s).

<table>
<thead>
<tr>
<th>Vehicle speed (m/s)</th>
<th>Truck</th>
<th>Truck with trailer</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>0.60</td>
<td>1.20</td>
</tr>
<tr>
<td>20</td>
<td>0.66</td>
<td>1.14</td>
</tr>
<tr>
<td>25</td>
<td>0.68</td>
<td>1.11</td>
</tr>
</tbody>
</table>

By increasing vehicle speed the estimated \( C_d \) increases for the rigid truck and decreases for the truck with trailer. An increased \( C_d \) by increasing vehicle speed is not supposed to be correct at the measurement conditions. One explanation to this incorrect speed relation could be that the true \( F_{trm} \) and \( F_r \) increase by speed. Since these forces have been expressed as constants the speed contributions have to go elsewhere i.e. to \( F_{air} \). The same argument is valid for truck with trailer. Because the air resistance is higher for the truck with trailer and more speed dependent the errors in \( F_{trm} \) and \( F_r \) are perhaps not big enough to cause decreasing \( C_d \) by increasing speed. If the size of \( F_{trm} \) and \( F_r \) are mainly correct then \( F_{air} \) including \( C_d \) for the rigid truck mainly should have a correct size level despite an incorrect speed dependency.

For the truck with trailer the \( C_d0 \) value is presented in table 6.1. One can, based on the literature (Hucho, 1987), expect the relative meteorological wind effect on \( C_d \) to be higher for the truck with trailer compared to just the truck.

One could then expect the \( C_d/C_d0 \) quote to be lower for the rigid truck compared to the truck with trailer at the same conditions.

In (Hucho, 1987) there is an example of side wind effects for a truck and for the same truck with trailer. The rigid truck proportion of the truck and trailer value increases by yaw angle. The proportion increases from 45 to 66% when the yaw increases from 5 to 15 degrees. If one then uses the \( C_d \) change by yaw from table 6.1 it is possible to estimate the \( C_d0 \) of the rigid truck. The estimated \( C_d0 \) of just the truck is still speed dependent: 0.42–0.57 at speed interval 15–25 m/s. At the speed of 20 m/s the truck \( C_d0 \)}
is estimated to 0.52. The average $C_{dt}$ value for the rigid truck then is estimated to 0.56 (wind speed 3 m/s and vehicle speed 20 m/s). The rigid truck $C_{db}$ and $C_{dt}$ values are most uncertain.

6.3 Discussion of measuring results

To find time periods with perfect meteorological conditions for coastdown measurements, wind speed close to zero for example, is not easy. Such a period needs to be long enough for including a complete measuring program. One must of practical reasons to some extent accept deviations from what is desired. These deviations should to some extent be possible to adjust for by means of adjustment expressions included in the driving resistance function. In order to adjust for wind there need to be measured wind speed and wind direction. The variation in meteorological wind speed during measurements needs to be more than minor if representative parameter values for wind adjustment will be possible to estimate. This is in contradiction to the first statement about desired wind speed close to zero. In the present study it seems that the variation in meteorological wind conditions has been big enough for the estimation of reliable parameters in the adjustment function.

One main problem in coastdown measurements is dependencies between the explanatory variables. There are some correlations also in the reduced data set which could cause problems in the analysis.

The observed driving patterns at coastdowns represent the true total driving resistance. This implies, if the driving pattern and the road gradient are measured without systematic errors, that when estimated parameters are used for estimations of the total driving resistance this estimation is expected to be representative for the true total driving resistance, at least in the calibration interval. Instead there might be doubts about separate estimated partial driving resistances.

The transmission losses estimation has the highest degree of uncertainty of the table 6.1 parameter estimations. The estimated $F_{trm}$ value (258 N) is most equal to values in literature at different vehicle speeds presented in table 5.6:

- 15 m/s: 245 N
- 20 m/s: 260 N.

The bearing resistance constitutes, based on the literature, approximately 10% of the estimated rolling resistance in table 6.1.

The estimation of representative air resistance parameters, for box vehicle body, is influenced both of shortcomings in the method used and peculiarities of the test vehicle.

In the measurement data the meteorological wind is available for one location at the test route. However, the wind conditions might change along the test route. Such a variation is expected because of terrain changes along the route. In the analysis the assumption is that measured meteorological values at one location, the one used, are valid all along the test route. Another lack in the meteorological data is different methods used 14/10 and 21/10.
The height of the trailer is 0.1 m higher than the height of the truck. This could disturb the laminar air streams on the top of the vehicle combination. If the laminar air stream is disturbed this will influence the air resistance parameter. A difference in height of this size is not unusual.\(^{22}\)

The gap between a truck and a trailer will influence \(Cd\). To what degree the gap in this case (1.70 m) is representative for box vehicles or not is unknown.

The change in \(Cd\) as a function of the yaw angle \(b\) includes sinus (function 5.1). This function approach locks the degrees of freedom when estimating the change in \(Cd\) for a change in \(b\). The derivate of \(Cd(b)\), with this approach, has a maximum for \(b\) equal to zero. In the literature the derivate of \(Cd\) does not have a maximum for \(b\) equal to zero. One alternative to the used function could be:

\[
Cd=Cd0*(1+Cd1*(1+\sin(b-\pi/2)))
\]

This approach, not tested, should give a result more similar to the literature.

The estimation of air resistance for just the truck in section 6.2 has resulted in a “\(Cd\)” increasing by vehicle speed. The parameter estimation gave a negative \(Cd1\) for the truck, i.e. also increasing \(Cd\) with increasing vehicle speed because the angle \(b\) decreases with increasing speed. One explanation to the increasing \(Cd\) could be that \(F_{trm}\) and \(F_{r}\) have not been expressed as functions of \(v\) when estimating \(Cd\). An increase in transmission and rolling resistance with speed not included when estimating \(Cd\) for the rigid truck will then appear elsewhere.

Comments about air resistance parameters estimated for the truck with trailer compared to box vehicles in the literature:

- \(Cd0\): the estimated value 0.83 for a vehicle of year model 2007 is higher compared to the literature max value (0.74) for year models around 1980 with wind deflectors, see section 5.8
- \(Cd1\): a bit below the (Hucho, 1987) example.

The estimated \(Cd0\) is 24% higher compared to the mid point (0.67) in the literature interval. Especially when the expected time reduction factor also is regarded the difference is remarkable. The estimated parameter \(Cd0\) also has an interval of confidence (+/- 7%) which does not include the literature value.

The estimated \(Cd0\) for just the truck (0.52) is almost equal to the min value from the literature for 1980, see section 5.8. Compared to the mid point in the literature interval (0.54), i.e. a reduction from 1980 to 2007, the estimated value can not be rejected.

The quote \(Cd0(\text{rigid truck})/Cd0(\text{truck with trailer})\) could be of some interest:

- the coastdown study (at 20 m/s): 0.62
- the literature: 0.81

One can, based on the literature, expect the quote to decrease when the length of the truck with trailer increases. The total length of the coastdown truck with trailer is 24 m, which probably is longer compared to vehicles the literature data is based on in average. This circumstance can be one explanation to the quote difference.

\(^{22}\) Information from Håkan Forsbäck, the truck driver (2011-02-25).
In table 6.2a–6.2c the importance of considering the meteorological wind is demonstrated. For average Swedish conditions \( C_{dt} \) is estimated to be 17% higher than \( C_{d0} \). The relative importance decreases with increasing vehicle speed.

The difference between the coastdown and the literature values could also be an expression for different measuring methods. Especially the yaw angle effect on air resistance is expected to be difficult to measure in a wind tunnel for a 24 m truck with trailer at scale 1:1. Also the big cross sectional area (11 m\(^2\)) of a box vehicle body could cause problem and need adjustments. Wind tunnel based \( C_d \) values are then expected to include adjustments. Such adjustments will probably induce increased uncertainties in wind tunnel values.

**Rolling resistance** data could in general be expected to be based on the ISO 18164 standard. For heavy vehicle tyres the standard tyre load should be 85% of maximum load capacity.

In this study a main proportion (70%) of the measurements are with unloaded vehicle. When loaded, the load factor has been 57%. This corresponds to a total vehicle weight 74% of the max allowed on the road. The estimated \( Cr \) values then should represent a tyre load below 85%. If \( Cr \) decreases with increasing load the estimated \( Cr \) values are expected to be overestimations compared to the standardized test method.

The trailer is equipped with an air suspension system, another suspension system compared to the truck. There are two aspects of interest about the air suspension system:

- the engine power needed to supply the system
- the roughness contribution to “rolling resistance”.

This air suspension system needs engine power compared to a leaf spring system. Another question is to what extent the air damping system compared to other suspension systems gives another driving resistance caused by road roughness. The first aspect is of interest when making simulation with the driving resistance parameters but it can not be estimated by coastdown measurements. If there is a systematic effect of the air suspension system on driving resistance this effect will be included in the \( iri \) parameters describing \( Cr \). Because there are different types of tyres on the truck and on the trailer there is no possibility in this study to isolate the effect of the air suspension system.

Estimated rolling resistance coefficients represent three tyre manufacturers on the truck and two on the trailer. The tyres on the trailer are super single tyres and on the truck they are conventional. There are three maximum speed- and load classes for the tyres on the truck. One can notice that the test tyres belong to the most frequent manufacturers for tyres on the road.

The mix of tyres from different manufacturers could in one way be a drawback and in another way an advantage. The advantage should be that estimated \( Cr \) constitutes a mean value for several frequent tyre models. The drawback is that \( Cr \) can not be estimated for one manufacturer or for one speed- or load class. In principal there is a possibility to distinguish between super single, the tyres on the trailer, and other tyres but the estimated parameters were not proved different from zero. This possibility is limited to the basic and \( mpd \) part of \( Cr \).
Rolling resistance parameters are dependent on ambient temperature. When comparing to measurements following the ISO standard, i.e. measurements at an ambient temperature of 25°C, this is of importance.

The variation in ambient temperature in the test data set is 4.2 to 5.8°C. This small interval could be one explanation for that the estimated parameter for temperature adjustment does not seem to be representative. The estimated Cr value without including temperature adjustment represents an ambient temperature of 5°C. Based on temperature adjustment in ISO 28 580 one can estimate Cr at 25°C to be 12% below the estimated value at 5°C. If Cr decreases with increasing temperature the estimated Cr value is expected to be an overestimation compared to the conditions in the ISO standard.

The trial to estimate the vertical load effect on Cr, see table J1b, has resulted in parameter values not significantly different from zero. An explanation for this result could be the correlations between vehicle mass and meteorological variables. One also can notice that tyre pressure has been estimated being lower 14/10, contributing to increased rolling resistance, compared to 21/10.

The vertical load effect on Cr described in (Rexeis et al, 2005) could not be proved based on the coastdown data. The expected decrease in Cr when increasing the load factor from 0 to 57% is 7%. The possibility to estimate an expected effect of this size can be considered with the confidence interval for Cr in table 6.1 is +/-15% as a background. A load factor effect was proved for the speed effect connected to iri on Cr, see table G2b.

The analysis including roughness and macro texture variables has not resulted in all parameters being significantly different from zero. The macro texture has a high correlation to the gradient in the total data set. After reduction of observations causing high correlation the Cr0 and Cr11 (iri) are proved different from zero but not Cr20 (mpd).

One reason for the estimated mpd effect not being significantly different from zero could be the narrow range of mpd on the test route: 0.68–0.92. Another reason for not proving an mpd effect could be that measured mpd by RST does not represent the position of the truck tyres completely. The left RST track should represent the truck wheels on the left vehicle side but the right RST-track is situated at least 0.3 m to the left of the wheels on the right side of the coastdown truck. In principle the same conditions are valid for iri but a difference in the wave length area could make a difference.

In (Hammarström et al., 2008) road surface effects on rolling resistance have been measured for three vehicle types: a car; a van (GVW 3.2 t) and a heavy truck (GVW 17.7 t). There seems to be a systematic change in road surface effects by vehicle size:

- the iri relative effect increases with increasing GVW
- the mpd relative effect decreases by increasing GVW.

If the results from this study are added to the one above the tendency is strengthened.

One further result of interest could be that the speed dependency of the the iri part of Cr might have an exponent less than 1, see table G2b.

The distribution of total rolling resistance on the basic part and the road surface effects depends on the selected data set, i.e. the total or the reduced data set. Even if there is a
logic reason for using the reduced data set in this situation the estimated rolling resistance parameters are judged to be less reliable. The situation is to some extent improved by the basic rolling resistance being approximately of the same size as values in the literature, when using the reduced data set.

There is not much information in the literature about road surface effects on heavy duty vehicles. The method used in this study should be more reliable compared to the method used for the HDV in (Hammarström et al., 2008).

The tyres on the test vehicle could be characterized as worn, see table A4. As a rough estimation the rolling resistance for the test vehicle, because of tyre wear (50%), could be expected to be reduced by 15%.

Estimated $Cr$ for the test vehicle including the tyre wear effect on a flat and smooth surface based on NOKIA and TÜV data respectively:
- the truck: $Cr0=0.0037$ and $0.0035$
- the trailer: $Cr0=0.0033$ and $0.0032$
- the equipage: $Cr0=0.0035$ and $0.0034$.

These values are not based on measurements including super single tyres. Super single tyres, used on the trailer, are expected to have lower $Cr0$ compared to the presented values. The estimated equipage $Cr0$ value $0.0038$ is close to values in the literature. One should notice the difference in ambient temperature, $5^\circ$C for coastdown and $25^\circ$C for the literature values.

What to include in “rolling resistance” is not quite obvious. This study includes for example bearing resistance and roughness resistance in rolling resistance. Roughness resistance represents energy losses both in the suspension system and in the tyres. For the same tyres one can expect different total roughness effects for different vehicles. If roughness and bearing resistance are included in rolling resistance one should note that rolling resistance does not only include tyre effects.

Increased crossfall ($crf$) should give increased side force and finally increased driving resistance. The estimated parameter, not significantly different from zero, has a minus sign instead of a plus sign. Possible explanations:
- high correlation ($crf$) to the gradient ($gr$)
- influence of side wind on the side force not included in the analysis
- influence of wheel tracks might change the vehicle side tilting from being equal to the cross fall
- influence of the horizontal radius not included in the analysis.

Including the horizontal radius and the side wind into the analysis could be a possibility to improve the estimation of $Cr3$. The estimated $Cr$ will in any case include the side force effect. The correlation between $crf$ and $gr$ is higher in the reduced data set than in the total data set.

This coastdown study could be of general interest of methodological reasons at some points:
- the demand for high accuracy of the road gradient
- the description of the continuously changing vehicle weight
- the systematic change in vehicle load in order to estimate transmission resistance but also the vertical load effect on rolling resistance
- the equipment used in order to measure the coastdown driving pattern
- the method used in order to separate parts of the driving resistance.
7 Comparison of measuring results with PHEM data

7.2 PHEM parameter values

One main objective with the coastdown study is to present data which can be used in order to update vehicle parameters used for estimation of emission factors in HBEFA. These emission factors have been estimated by use of the PHEM simulation model. The parameter values in PHEM should represent:

- average vehicles per vehicle segment and emission concept (year model interval)
- average meteorological conditions
- average road surface conditions per area and road type.

As a general rule all conditions of more than “minor” importance for driving resistance should be included in the parameter values used for PHEM simulations.

The HGV segments of interest are the ones represented in the coastdown study:

- truck with trailer GVW 50–60 t
- rigid truck GVW 26–28 t.

The emission concept of special interest is euro 4, the concept of the coastdown truck.

The possibility to judge the degree of representativeness of PHEM values is based on the available sources of information: the coastdown study and the literature. Comments about these two sources:

- the coastdown just represents one truck with trailer and one rigid truck
- the literature survey does not fulfil the scientific demands in a systematic way covering all important data bases until today.

There are two ways to comment on PHEM parameters:

- the conditions the parameter values are claimed to represent
- the average conditions out on the roads they should represent.

The PHEM parameter values to compare with other data sources are presented in section 5.8.

7.2 Comparison of PHEM parameters with the coastdown study and with the literature

The transmission losses in PHEM are described by separate functions for the gear box and for the differential (final gear box). These functions include both mechanical and churning losses in parallel.

In table 5.7 transmission churning losses based on PHEM have been estimated for vehicle parameters equal to the test vehicle in the coastdown study.
Comments about $Ftrm$:

- PHEM estimations are directly proportional to a change in $Prat$, corresponding to the functions in (Carlsson, 2008)
- PHEM values are just a bit below the levels in (Carlsson, 2008) and in the coastdown study
- PHEM estimations are speed dependent but not the other two sources of information.

The conclusion about $Ftrm$ in PHEM: there is no indication that the model used including parameter values is not representative. One can not exclude the possibility for $Ftrm$ being speed dependent.

The **rolling resistance** in PHEM is a function of:

- rigid truck or truck with trailer
- GVW
- load factor.

What is not explicitly included in PHEM for example:

- road surface conditions, $iri$ and $mpd$
- meteorological conditions:
  - road surface: water, snow and ice
  - Other: ambient temperature and pressure
- separate values for free rolling wheels or drive wheels.

In table 7.1 estimated rolling resistance values from coastdown and values used in PHEM are presented in parallel.
Table 7.1 Rolling resistance (Cr) from coastdown compared to PHEM values.

<table>
<thead>
<tr>
<th>Surface</th>
<th>Coastdown (truck with trailer)*</th>
<th>PHEM**</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Speed (m/s) Rigid Truck with</td>
<td></td>
</tr>
<tr>
<td>iri</td>
<td>mpd</td>
<td>10</td>
</tr>
<tr>
<td>0</td>
<td>0.0037</td>
<td>0.0037</td>
</tr>
<tr>
<td>1</td>
<td>0.0053</td>
<td>0.0058</td>
</tr>
<tr>
<td>2</td>
<td>0.0060</td>
<td>0.0064</td>
</tr>
<tr>
<td>1 1</td>
<td>0.0062</td>
<td>0.0072</td>
</tr>
<tr>
<td>2 2</td>
<td>0.0069</td>
<td>0.0078</td>
</tr>
</tbody>
</table>

Examples for different iri and mpd values.

On the test route for coastdown.

<table>
<thead>
<tr>
<th>1.2</th>
<th>0.81</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0054</td>
<td>0.0059</td>
</tr>
</tbody>
</table>

* The coastdown if is on two levels: 0 and 57%; Tread wear approximately 50%; Ambient temperature 5° C; **lf: 0-100%; decreasing Cr with increasing wheel load;

From table 7.1 it looks like PHEM Cr is close to the coastdown Cr on the test route. Especially for rural speed conditions the values are approximately equal. For urban speed conditions (low speed) the PHEM values are higher compared to the coastdown.

For roads with iri and mpd equal to 2 and 1, as an example, the PHEM value for a truck with trailer at 20 m/s will be at least 16% below the coastdown value.

The PHEM values have not explicitly been adjusted for road surface conditions.

Expected Cr0 values on a flat and smooth surface for new tyres based on the literature:

- rigid truck GVW 26–28 t (1 drive axle and 2 free rolling axles): 0.0042
- truck with trailer GVW 50–60 t (1 drive axle and 6 free rolling axles): <0.0040 (no super single tyres included in the estimation)

The agreement between the coastdown values and the literature values is good for a flat and smooth road surface, also considering the influence of tyre wear.

Especially if PHEM data is supposed to represent a smooth and plane surface (iri=0 and mpd=0) Cr used is considerably higher than in the literature. On a flat and smooth road surface PHEM values seem to be “overestimations”. On the other hand the “overestimations” seem to have used values more equal to real road conditions.

The average Cr for a rigid truck is expected to be higher compared to Cr for a truck with trailer because the drive axle Cr is higher compared to axles with free rolling wheels. The average Cr for free rolling wheels are expected to be lower for a truck with trailer because higher share of super single tyres.
The PHEM $Cr$ for a rigid truck is higher than for a truck with trailer, as expected. In reference (Rexeis et al., 2005) the only variable used for selection of $Cr$ is the vertical load. Based on the documentation it is not obvious why PHEM $Cr$ is higher for the rigid truck than for the truck with trailer.

The **air resistance** parameters presented in table 5.9 are used for HGV simulations in PHEM representing all types of vehicle bodies. There are two types of vehicle data needed for the simulation of air resistance: the aerodynamic qualities of the vehicle body and the cross section area.

The PHEM values do not include any meteorological wind effects described in the documentation but they are used for estimation of total air resistance. Total air resistance on the road includes meteorological influence.

The air resistance is influenced by meteorological wind in two ways:

- a change in average resulting wind
- a change in $Cd$ depending on a change in the yaw angle ($b$).

The first point does not have any demand on parameter values. The only need is average meteorological wind i.e. wind direction distribution and speed. An example on this effect is presented in table 6.2b.

By not including meteorological wind in the air resistance description two effects are expected for just the air resistance:

- an underestimation of air resistance
- an overestimation of the speed dependency.

Since the coastdown truck belongs to euro 4 the PHEM and the literature values have been adjusted to represent this emission concept by use of correction factors included in PHEM.

The air resistance coefficients used in PHEM are possible to comment on based on an air resistance literature survey (Hammarström, 1999):

- For the same type of vehicle body one can expect $Cd0$ to increase from a truck to a truck with semitrailer
- For the same type of vehicle body one can expect $Cd0$ to increase from a truck with semitrailer to a truck with trailer
- The only main type of vehicle body with an air resistance coefficient below or equal to the box value is the tanker
- For all other main groups of vehicle bodies (flat; timber; tipper) one can expect air resistance coefficients at least as high as for the box type.

The PHEM values are supposed to represent an average for all type of vehicle bodies. In order to estimate how representative PHEM values are most rough estimations for all vehicle bodies have been made for what has been assigned “coastdown” and “literature”. Vehicle bodies have been categorized into box, other and all. The method used:
The mileage distribution for trucks with trailer has been estimated with 50% on box vehicle bodies and 50% on other types, see table 5.1. For rigid trucks assume less portion on box, 33%, and 67% on other.

Based on the literature the $C_d0$ for the group of other vehicle bodies is estimated in average to be approximately 25% higher than for box.

Assumed that the literature 25% increase for other vehicle bodies is valid also for the coastdown alternative

Assumed that $C_d t/C_d0$, the relative meteorological wind effect, estimated by coastdown, is valid also for other truck with trailer vehicle bodies

Based on (Hucho, 1987) $(C_d t/C_d0-1)$ for a rigid truck is estimated to 0.45–0.66 of $(C_d t/C_d0-1)$ for yaw 5–15° for a truck with trailer at average conditions

By combining the conditions specified, $C_d0$ and $C_d t$ are possible to estimate for two groups of vehicle bodies: box and other. The total fleet segment average is assigned by “all”.

Estimated $C_d0$ and $C_d t$ values are presented in table 7.2 and 7.3.

Table 7.2 Average resistance parameters ($C_d0$) at a meteorological wind of 0 m/s. Euro 4.

<table>
<thead>
<tr>
<th>Segment</th>
<th>Coastdown</th>
<th>Literature</th>
<th>PHEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Box vehicle body</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Truck w. tr. GVW 50–60t</td>
<td>0.83</td>
<td>0.61</td>
<td>–</td>
</tr>
<tr>
<td>Rigid tr. GVW 26–28t</td>
<td>0.52</td>
<td>0.49</td>
<td>–</td>
</tr>
<tr>
<td>All vehicle bodies</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Truck w. tr. GVW 50–60t</td>
<td>0.94</td>
<td>0.69</td>
<td>0.62</td>
</tr>
<tr>
<td>Rigid tr. GVW 26–28t</td>
<td>0.61</td>
<td>0.58</td>
<td>0.63</td>
</tr>
</tbody>
</table>

*Adjusted to euro 4 based on PHEM corrections.

Table 7.3 Average resistance parameters ($C_d t$) at a vehicle speed of 20 m/s and a meteorological wind of 3 m/s. Euro 4.

<table>
<thead>
<tr>
<th>Segment</th>
<th>Coastdown*</th>
<th>Literature*</th>
<th>PHEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Box vehicle body</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Truck w. tr. GVW 50–60t</td>
<td>0.97</td>
<td>0.72</td>
<td>–</td>
</tr>
<tr>
<td>Rigid tr. GVW 26–28t</td>
<td>0.56</td>
<td>0.53</td>
<td>–</td>
</tr>
<tr>
<td>All vehicle bodies</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Truck w. tr. GVW 50–60t</td>
<td>1.10</td>
<td>0.81</td>
<td>0.62</td>
</tr>
<tr>
<td>Rigid tr. GVW 26–28t</td>
<td>0.67</td>
<td>0.62</td>
<td>0.63</td>
</tr>
</tbody>
</table>

*Including all meteorological wind effects described in section 3. The angle (a) between the speed wind and meteorological wind is assumed to be uniformly distributed around the horizon. The literature meteorological wind effect is based on the coastdown results and adjustments to euro 4 are based on PHEM values.
Comments to table 7.2 and 7.3 about $Cd_0$ and $Cdt$

- Both coastdown and the literature indicate higher values for truck with trailer than for rigid truck on the contrary to PHEM.
- $Cd_0$: PHEM values compared to other sources are lower for truck with trailer and higher for rigid truck.
- $Cdt$: PHEM values are considerably lower for truck with trailer and approximately at the same level for rigid truck compared to other sources.

There are two sets of vehicle parameter values used for air resistance estimation: $Cd$ and the cross section area $Ayz$.

$Ayz$ values used in PHEM are presented in table 5.11. For Swedish conditions $Ayz$ has been estimated:

- for box vehicle body, the same values as in the coastdown study
- for other vehicle bodies than box: approximately equal to the cabin cross area, 9.0 m$^2$
- for mileage distribution on different types of vehicle bodies equal to what is used for $Cd_0$ and $Cdt$ estimations.

One frequent vehicle body is for timber transports (bunks), see table 5.1. For this vehicle body there is a wall between the cabin and the load area. The height of this wall is almost equal to the max load height. For the timber trucks there is approximately no difference in $Ayz$ between full loaded and no load. The cross section area for timber trucks should be approximately equal to the box cross section area. This has not been considered when estimating $Ayz$ to 9.0 m$^2$ for the other group, i.e. an underestimation.

In table 7.4 and 7.5 estimated cross sectional areas for Swedish conditions are presented in parallel with PHEM values.

### Table 7.4 Cross sectional areas (m$^2$) for truck with trailers GVW 50–60t, euro 4.

<table>
<thead>
<tr>
<th>Source</th>
<th>Vehicle body</th>
<th>box</th>
<th>other</th>
<th>all</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHEM</td>
<td></td>
<td></td>
<td></td>
<td>8.1</td>
</tr>
<tr>
<td>Coast d. (Swedish)</td>
<td></td>
<td>11.2</td>
<td>9.0</td>
<td>10.1</td>
</tr>
</tbody>
</table>

### Table 7.5 Cross sectional areas (m$^2$) for rigid trucks GVW 26–28t, euro 4.

<table>
<thead>
<tr>
<th>Source</th>
<th>Vehicle body</th>
<th>box</th>
<th>other</th>
<th>all</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHEM</td>
<td></td>
<td></td>
<td></td>
<td>7.5</td>
</tr>
<tr>
<td>Coast d. (Swedish)</td>
<td></td>
<td>11</td>
<td>9.0</td>
<td>9.7</td>
</tr>
</tbody>
</table>

The PHEM values are considerably lower, approximately 20%, compared to coastdown values (Swedish).

In table 7.6 and 7.7 the product of the cross sectional area and $Cd_0$ and $Cdt$ respectively are presented. Since there is no available literature cross section values the literature products are based on: the coastdown study estimation and the PHEM values. The coastdown study cross section values are used as the main alternative for literature.
Table 7.6 “Air resistance” \( Cd_0 \times A_{yz} \), Euro 4.

<table>
<thead>
<tr>
<th>Veh. segment</th>
<th>Coastdown</th>
<th>Literature*</th>
<th>PHEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Box vehicle body</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Truck w. tr. GVW 50–60t</td>
<td>9.3</td>
<td>6.9/(5.0)</td>
<td></td>
</tr>
<tr>
<td>Rigid tr. GVW 26–28t</td>
<td>5.7</td>
<td>5.4/(3.7)</td>
<td></td>
</tr>
<tr>
<td>All vehicle bodies</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Truck w. tr. GVW 50–60t</td>
<td>9.5</td>
<td>7.0/(5.6)</td>
<td>5.1</td>
</tr>
<tr>
<td>Rigid tr. GVW 26–28t</td>
<td>5.9</td>
<td>5.6/(4.3)</td>
<td>4.8</td>
</tr>
</tbody>
</table>

* Coastdown cross section area/(PHEM cross section area); Adjusted to euro 4 based on PHEM corrections.

Table 7.7 “Air resistance” \( C_d \times A_{yz} \) including average meteorological wind effect at 20 m/s. Euro 4.

<table>
<thead>
<tr>
<th>Veh. segment</th>
<th>Coastdown</th>
<th>Literature*</th>
<th>PHEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Box vehicle body</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Truck w. tr. GVW 50–60t</td>
<td>10.9</td>
<td>8.1/(5.8)</td>
<td></td>
</tr>
<tr>
<td>Rigid tr. GVW 26–28t</td>
<td>6.2</td>
<td>5.9/(4.0)</td>
<td></td>
</tr>
<tr>
<td>All vehicle bodies</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Truck w. tr. GVW 50–60t</td>
<td>11.1</td>
<td>8.2/(6.6)</td>
<td>5.1</td>
</tr>
<tr>
<td>Rigid tr. GVW 26–28t</td>
<td>6.5</td>
<td>6.0/(4.7)</td>
<td>4.8</td>
</tr>
</tbody>
</table>

* Coastdown cross section area/(PHEM cross section area; Adjusted to euro 4 based on PHEM corrections).

PHEM \( C_d \times A_{yz} \) for all vehicle bodies compared to the other sources:
- truck with trailer: 38–54% lower values
- rigid truck: 21–27% lower values.

Then, at a vehicle speed of 20 m/s and \( lf=50\% \), PHEM will under estimate the total driving resistance for a truck with trailer by 16–27%.

7.3 Discussion about PHEM parameters compared to the literature and the coastdown study

The churning transmission losses are at the same level as the other two sources of information. The coastdown estimation is most uncertain and the other literature reference is not that well documented. Still these three independent sources have approximately the same level.

The rolling resistance parameters used in PHEM is judged to be acceptable for average Swedish road conditions. If this acceptable level is just a coincidence the model used is not acceptable for future estimations of emission factors. The \( Cr \) road surface
contribution to total rolling resistance at 20 m/s on the test route is estimated to approximately 40%.

There is a systematic difference in $Cr$, higher for the tyres on the drive axle than the tyres on the other axles. In PHEM a rigid truck has higher $Cr$ compared to a truck with trailer which could be an expression for the same systematic difference. However, the documentation does not include any information about this.

The $Cr$ model used needs to be transparent enough for future descriptions of changing conditions including road surface. There also could be a demand for estimation of regional and national $Cr$ values since at least the road surface contribution is expected to vary more than marginally between regions and nations.

In order to use a $Cr$ model including the road surface influence there is need for statistics on iri and mpd for the road network. Such information is available.

The air resistance estimation in PHEM is probably an underestimation especially for Swedish conditions.

The underestimate based on the coastdown study at 20 m/s and a meteorological wind 3 m/s for an average vehicle per segment ($C_{dt}$):

- 43% for a truck with trailer
- 5% for a rigid truck.

The underestimate based on the “literature” for the average Swedish conditions:
- 23% for truck with trailer
- 2% for rigid truck.

The differences between PHEM and the other sources is both an expression for different $Cd_0$ values and not including meteorological wind in PHEM. Including the cross sectional area in the analysis the PHEM underestimation for all vehicle bodies based on the coastdown study could be:

- 55% for truck with trailer
- 28% for rigid truck.

The underestimate based on the “literature” for the average Swedish conditions:

- 39% for truck with trailer
- 24% for rigid truck.
8 Discussion on a total level

The parameter estimation in this study is based on coastdown on the road measurements. Most driving resistance parameter values in the literature are based on laboratory measurements: rolling resistance on drums; air resistance in wind tunnels etc.

The advantages with the coastdown study compared to laboratory values could be:

- the total measured driving resistance is expected to have a big potential for being accurate on condition that the speed profile and gradient are accurate
- estimated values are representative for conditions out on real roads
- the cost for measuring equipment is comparatively low compared to the other alternatives.

The drawbacks with coastdown could be:

- there might be problems trying to isolate the different driving resistance parameters
- all conditions of potential importance for the driving resistance need to be recorded
- measurements probably need to be more extensive compared to laboratory measurements
- rolling resistance can not be measured for a single tyre
- there is need for adjustment functions since most conditions can not be controlled.

The need for emission factor simulation is parameters representative for all vehicle bodies and tyres per emission concept in the HGV segments. Driving resistance parameters have been estimated by means of measurements for two vehicle equipage, rigid truck and truck with trailer, with one type of vehicle body. There is a similar problem about the tyres used. Based on these measured data and data in the literature parameter values for average vehicles have been estimated.

Comments about the method used for air resistance:

- \( Cd0 \) for HGV 50–60 t box vehicle body: the big deviation between the coastdown value and the literature need to be controlled by additional measurements
- \( Cdt \) for HGV 50–60 t and other frequent vehicle bodies: if the coastdown \( Cd0 \) for a box vehicle body is representative there is need for additional coastdown measurements with other frequent vehicle bodies in the HGV 50–60 t segment
- \( Ayz \): there is need for a more systematic method for estimation of different frequent vehicle bodies than what has been used in the coastdown study
- \( Mileage \): the empirical data used are from 1997, i.e. there is need for more present data.
Of course one cannot exclude there being a similar need also for other vehicle categories and segments than rigid truck 26–28 t and truck with trailer 50–60 t.

For simulation purpose there is a need for rolling resistance both on the drive axle at drive conditions and for free rolling wheels. This study has estimated rolling resistance values for free rolling wheels. The rolling resistance at drive conditions, the drive axle, is expected to be higher compared to free rolling wheels. One part of this additional rolling resistance at driving mode constitutes slip energy. This slip resistance has been estimated to be most marginal.23

Calculations are roughly based on three main groups of data:

- power train including the engine
- other vehicle data:
  - masses
  - vehicle parameters
- driving patterns24.

In order to reach representative emission factors all these groups of data need to be representative. The need of data in each group should be a function of the standard deviation in each group of data and the lack of data.

In the COST 346 and in the ARTEMIS projects big efforts have been made on developing a data base for HDV engines based on measurements. The cost for the measurements of one engine could be approximately 50 000 euro. Measurements of driving patterns were also included in COST 346 and ARTEMIS. Vehicle parameters used in PHEM for emission factor simulation have mainly been based on literature data. The cost for coastdown measurements in order to estimate vehicle parameters is estimated to approximately 10 000 euro for one vehicle.

Available restricted resources need to be distributed on the three main groups of data in a way that maximizes the representativeness of simulated emission factors at the lowest cost.

\[ F_{slip} = \frac{(F_{xwh} - F_{rwh})^2}{C_s} \]

\( F_{slip} \): additional resistance per drive wheel caused by longitudinal slip. (N)

\( F_{xwh} \): driving resistance distributed per drive wheel. (N)

\( F_{rwh} \): rolling resistance per drive wheel. (N)

\( C_s \): slip coefficient. (N)

23 The driving pattern is influenced of the road surface in two ways: physical and by driving behaviour. An iri increase of one unit is expected to reduce speed by 2.3 km/h. (Ils and Velin, 2002).
9 Conclusions

Conclusions about the coastdown method used:

- The registration of meteorological conditions at just one point is not satisfying
- The use of V-box for the speed profile simplifies measurements and reduces the total cost in a considerable way without reducing accuracy
- The difference between road surface measurements and tyre exposure is not satisfying
- The high accuracy in gradient measurements is of great importance
- In order to estimate the influence of all variables of importance including the meteorological part there need to be an area of variation big enough. This is to some extent in contradiction to general rules for coastdown measurements
- Tyre pressure control is at least a practical problem difficult to handle with the budget constraint especially for truck with trailer
- The total measured driving resistance should be accurate and without systematic errors under the condition that the speed profile and the gradient are without systematic errors.

Conclusions concerning estimated vehicle (box vehicle body) parameter values based on the coastdown study:

- Transmission churning losses: the estimation seems uncertain, there is a wide confidence interval (+/-95%), but is at the same level as is found in the literature including what is used in PHEM
- Rolling resistance: the split of $Cr$ into a basic part ($Cr0$), an $iri$ part and an $mpd$ part includes a more than minor uncertainty with the $mpd$ parameter not significantly different from zero. However, the $Cr0$ part is in accordance with the literature. At least the sum of the road surface effects, which constitutes approximately 40% of total $Cr$ on the test route at 20 m/s, seems to be representative. Contribution to the uncertainty in the estimated road $mpd$ effect is the narrow $mpd$ interval on the test route and the difference between measured tracks with RST and the conditions in the test vehicle wheel tracks
- Bearing resistance is included in the rolling resistance and constitutes approximately 10%
- Air resistance:
  - truck with trailer: both $Cd0$ and $Cd1$ are estimated with at least acceptable accuracy; $Cd0$ is more than 20% higher compared to 1980 literature values. Considering average Swedish conditions concerning vehicle speed and meteorological wind speed, air resistance is estimated to increase by 17%
  - rigid truck: most uncertain $Cd0$ estimation; the estimated value is as expected below the 1980 literature value
  - one part of the meteorological wind effect is possible to estimate without the use of $Cd1$
- If $(n-1)$ of part resistances are correct, the $nth$ part should as well be correct when the total measured resistance is expected to be correct.
The big difference in $Cd0$ between the literature and the coastdown estimations for truck with trailer indicates a need for a deeper analysis of the reason behind. One can not exclude the possibility for the coastdown value to be the most representative alternative. One explanation to the difference could be that the vehicles in the literature are shorter than the test vehicle (24 m).

If the estimated $Cd$ is correct there should be a considerable need for additional coastdown measurements of typical vehicle bodies in the segment HGV 50–60 t.

Conclusions concerning PHEM parameter values, used for HBEFA emission factor estimation, and the methodology behind:

- Parameter values need to be representatively based on a reliable method used for estimation
- There is no indication that the churning part of transmission losses is not representative
- The road surface effect part of rolling resistance, which constitutes approximately 40% of the total $Cr$ value, could need to be considered in a more systematic way
- There is a systematic difference between $Cr$ for driving wheels and free rolling wheels which need to be noticed
- The $Cdt$ used could be an underestimation up to:
  - 43% for a truck with trailer
  - 5% for a rigid truck.
- The cross sectional area $Ayz$ could be an under estimation of approximately 20%
- The $Cdt*Ayz$ used could be an underestimation up to:
  - 54% for truck with trailer
  - 28% for rigid truck.
- The PHEM total driving resistance at 20 m/s constant speed and $lf=50\%$ for a truck with trailer underestimates driving resistance by 27% if the coastdown based estimations would be representative.

Based on the literature the indicated underestimation of air resistance in PHEM will decrease compared to the coastdown alternative. One should observe that more “simple” input data like the cross sectional area is of the same importance as $Cd$ for driving resistance estimation. The cost for representative estimations of cross sectional area is considerable lower compared to measurements of $Cd$.

In the HBEFA improvement work it should be important to make additional coastdown measurements with the most frequent vehicle bodies in the HGV category including the most important size segments. One can not exclude there being a similar need for other vehicle categories. Such expanded mapping of vehicle parameters needs to be done inside a well planed and organized measuring program.
List of references


Evéquoz R. Emissionsfaktoren von schweren Motorwagen in der Schweiz, Schlußbericht; Bundesamt für Umwelt, Wald und Landschaft (BUWAL); Umwelt-Materialien Nr. 38; Luft:Bern 1995

Fine Offset Electronics. V box.


Racelogic VBOX. VBOX 3i, 100 Hz GPS Datalogger. Buckingham. 2009.


List of variables

\(a\): angle between vehicle length axis and \(vl\) (rad)

\(A(b)\): the vehicle cross section area orthogonal to resulting wind at yaw equal to \(b\).

\(Axz\): the projected side area (m²)

\(Ayz\): the projected frontal area of the vehicle (m²)

\(b\): the yaw angle between vehicle length axis and \(vlr\) (rad)

\(C_A\): the tyre stiffness (N/rad)

\(Cb\): coefficient for bearing resistance

\(Cd\): the air dynamic coefficient (dimensionless)

\(Cd0\): the air dynamic coefficient when \(a=0\)

\(Cd1\): adjustment parameter for wind direction deviating from driving direction

\(Cd1'\): adjustment parameter for resulting wind direction deviating from direction of speed wind and a projected area orthogonal to resulting wind.

\(Cd_t\): the air dynamic coefficient including all meteorological wind effects

\(Cr\): parameter for total rolling resistance

\(Cr0\): parameter for base rolling resistance on a plane and smooth surface

\(Cr0D\): parameter for base rolling resistance on a a drum with a smooth surface

\(Cr01, Cr10, Cr11, Cr20 and Cr21\): additional rolling resistance for the road surface iri and mpd

\(Cr3\): parameter for sideforce resistance (1/N)

\(Cra\) and \(Crb\): parameters used for expressing the influence from different conditions on \(Cr\)

\(crf\): the crossfall (%)

\(Crz0\), \(Crz1'\) and \(Crz'\): parameters for expressing \(Cr\) as a function of the vertical load

\(D\): the diameter of the drum (m)

\(dns\): the density of air (kg/m³)

\(dv/dt\): the acceleration level (m/s²)

\(F_{acc}\): acceleration resistance from vehicle mass (N)

\(Fair\): air resistance (N)

\(Fb\): bearing resistance (N)

\(Fgr\): gradient resistance (N)

\(Fr\): rolling resistance (N)

\(F_{r,iri}\): additional driving resistance caused by road roughness (N)

\(F_{r,mpd}\): additional driving resistance caused by road macro texture (N)

\(F_{side}\): resistance caused by the side force (N)

\(F_{trm}\): transmission resistance (N)
fxl: a help variable in order to simplify the work with the parameter estimation

$F_y$: the side force acting on the vehicle (N)

gr: the longitudinal slope (rad)

$h$: the height of the truck or the truck with trailer (m).

$I16$: the gear ratio in gear position 16.

$iri$: the road roughness measure (mm/m)

$J$: the inertial moment per wheel ($\text{kgm}^2$)

$K_J$: (set to 1.0) is a correction factor of $J$ to include moving parts in the transmission system.

$L$: the total length of the truck or the truck with trailer (m).

$lf$: load factor (%)

$m$: the total mass of the vehicle (kg)

$macc$: acceleration mass

$m_j=\sum(K_j \cdot J/r_{wh}^2)$: where sum means summation over the wheels (kg)

$Moist$: the outdoor humidity (%RH)

$mpd$: the macrotexture measure (mm)

$Mxw$: is the maximum allowed load per tyre (N)

$nr$: engine speed (rpm)

$nrat$: engine speed at $P_{rat}$ (rpm)

$nrk$: rotation speed of the differential incoming axle (rpm)

$n_{wheel}$: rotational wheel speed (rpm)

$Pair$: the air pressure (mbar)

$Pair0$: air pressure at occasion 0 (mbar)

$Pair1$: air pressure at occasion 1 (mbar)

$Pbx$: differential churning losses (W)

$P_{diff}$: total power losses in the differential (W)

$P_{dr}$: power to overcome the driving resistances (without transmission losses) (W)

$P_{rat}$: max engine power (W)

$Pvx$: gear box churning losses (W)

$Pw0$: tyre over pressure at occasion 0 (bar)

$Pw1$: tyre over pressure at occasion 1 (bar)

$R$: the radius of the road curvature (m)

$rFmxv$: is the relative load per tyre (N/N)

$r_{wh}$: the wheel radius (m)

$T$: the ambient air temperature ($^\circ\text{C}$)
$Tw_0$: tyre temperature at occasion 0 (°C)

$Tw_1$: tyre temperature at occasion 1 (°C)

$trm$: a constant representing transmission resistance (N)

$v$: the vehicle velocity (m/s)

$vl$: meteorological wind speed (m/s)

$v_{lr}$: resulting wind speed from meteorological wind and vehicle speed wind (m/s)
Description of test vehicles

Table A1 Test vehicle data included in the Swedish vehicle register.

<table>
<thead>
<tr>
<th>Register data</th>
<th>Truck Model VOLVO FH16-580 6x2</th>
<th>Trailer Model VAK V-4-40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year model</td>
<td>2007</td>
<td>2007</td>
</tr>
<tr>
<td>First time in traffic</td>
<td>2006-11-17</td>
<td></td>
</tr>
<tr>
<td>Weight: max gross veh (kg)</td>
<td>27000</td>
<td>36000</td>
</tr>
<tr>
<td>Tax weight (kg)</td>
<td>26000</td>
<td>36000</td>
</tr>
<tr>
<td>Weight: “tjänstevikt” (kg)</td>
<td>13110</td>
<td>10090</td>
</tr>
<tr>
<td>Weight: max load (kg)</td>
<td>13890</td>
<td>25910</td>
</tr>
<tr>
<td>Allowed max load (kg)</td>
<td>12890</td>
<td>25910</td>
</tr>
<tr>
<td>Max weight trailer (kg)</td>
<td>44000</td>
<td></td>
</tr>
<tr>
<td>Max allowed equipage weight (kg)</td>
<td>70000</td>
<td></td>
</tr>
<tr>
<td>Guaranteed axle/boggie pressure 1</td>
<td>8000</td>
<td>18000</td>
</tr>
<tr>
<td>Guaranteed axle/boggie pressure 2</td>
<td>19000</td>
<td>18000</td>
</tr>
<tr>
<td>Fuel tank (dm³)</td>
<td>610</td>
<td></td>
</tr>
<tr>
<td>Gear box</td>
<td>Automatic. 12 gear positions</td>
<td></td>
</tr>
<tr>
<td>Max width (m)</td>
<td>2.6</td>
<td>2.6</td>
</tr>
<tr>
<td>Length of box (m)</td>
<td>7.370</td>
<td>12.35</td>
</tr>
<tr>
<td>Length total (m)</td>
<td>10.1</td>
<td>14.6</td>
</tr>
<tr>
<td>Number of axels</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Distance between axels 1-2 (m)</td>
<td>4.8</td>
<td>1.36</td>
</tr>
<tr>
<td>Distance between axles 2-3 [m]</td>
<td>1.37</td>
<td>6.72</td>
</tr>
<tr>
<td>Distance between axles 3-4 (m)</td>
<td>-</td>
<td>1.82</td>
</tr>
<tr>
<td>Tyre dimension axel 2 register</td>
<td>315/80R22,5</td>
<td>445/45R19,5</td>
</tr>
<tr>
<td>Power (kW) (ISO)</td>
<td>426.00</td>
<td></td>
</tr>
<tr>
<td>Vehicle body</td>
<td>box</td>
<td>box</td>
</tr>
</tbody>
</table>

*Width including measuring equipment. **Excluding measuring equipment.
### Table A2 Additional vehicle data not in the Swedish vehicle register

<table>
<thead>
<tr>
<th>Number of wheels per axle</th>
<th>Truck</th>
<th>Trailer</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;2-4-2&quot;</td>
<td>&quot;2-2-2-2&quot;</td>
<td></td>
</tr>
<tr>
<td>Inertial moment per wheel 1st axis (kgm$^2$)*</td>
<td>15.00</td>
<td>20.00</td>
</tr>
<tr>
<td>Inertial moment per wheel 2nd axis (kgm$^2$)*</td>
<td>12.50</td>
<td>20.00</td>
</tr>
<tr>
<td>Inertial moment per wheel 3rd axis (kgm$^2$)*</td>
<td>15.00</td>
<td>20.00</td>
</tr>
<tr>
<td>Inertial moment per wheel 4th axis (kgm$^2$)*</td>
<td></td>
<td>20.00</td>
</tr>
<tr>
<td>Wheel circumference 1st axis (m)</td>
<td>3.04</td>
<td>2.98</td>
</tr>
<tr>
<td>Wheel circumference 2nd axis (m)</td>
<td>3.11</td>
<td>2.98</td>
</tr>
<tr>
<td>Wheel circumference 3rd axis (m)</td>
<td>3.04</td>
<td>2.98</td>
</tr>
<tr>
<td>Wheel circumference 4th axis (m)</td>
<td>-</td>
<td>2.98</td>
</tr>
<tr>
<td>Height (m)</td>
<td>4.35</td>
<td>4.45</td>
</tr>
<tr>
<td>Projected vertical area (m$^2$)</td>
<td>11.0</td>
<td>11.2</td>
</tr>
</tbody>
</table>

*Information from Staffan Nordmark, VTI.

Distance between truck and trailer: 1.70 m. (the gap between the end of the truck box and the front of the trailer box.

### Table A3 Tyre specifications for the test vehicle

<table>
<thead>
<tr>
<th>Axis</th>
<th>Manufacturer</th>
<th>Model</th>
<th>Width/height (mm/%)</th>
<th>Radius (inches)</th>
<th>Speed class</th>
<th>Load index/max load (/N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Truck</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>MICHELIN</td>
<td>XFA2 ENERGY</td>
<td>385/55</td>
<td>R 22.5</td>
<td>L</td>
<td>185/90743</td>
</tr>
<tr>
<td>2</td>
<td>YOKOHAMA</td>
<td>SY397 Super Steel</td>
<td>315/70</td>
<td>R 22.5</td>
<td>M</td>
<td>148-152/36624</td>
</tr>
<tr>
<td>3</td>
<td>DUNLOP</td>
<td>SP252</td>
<td>385/55</td>
<td>R 22.5</td>
<td>K</td>
<td>160/36624</td>
</tr>
<tr>
<td>Trailer</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>DUNLOP</td>
<td>SP252</td>
<td>435/50</td>
<td>R 19.5</td>
<td>J</td>
<td>160/44145</td>
</tr>
<tr>
<td>2</td>
<td>KUMHO</td>
<td>KLT 01</td>
<td>435/50</td>
<td>R 19.5</td>
<td>J</td>
<td>160/44145</td>
</tr>
<tr>
<td>3</td>
<td>DUNLOP</td>
<td>SP252</td>
<td>435/50</td>
<td>R 19.5</td>
<td>J</td>
<td>160/44145</td>
</tr>
<tr>
<td>4</td>
<td>DUNLOP</td>
<td>SP252</td>
<td>435/50</td>
<td>R 19.5</td>
<td>J</td>
<td>160/44145</td>
</tr>
</tbody>
</table>
### Table A4  Tyre tread depth (mm)

<table>
<thead>
<tr>
<th>Axle</th>
<th>Left side</th>
<th>Right side</th>
</tr>
</thead>
<tbody>
<tr>
<td>Truck</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>8.1</td>
<td>7.7</td>
</tr>
<tr>
<td>2</td>
<td>3.7</td>
<td>4.5</td>
</tr>
<tr>
<td>3</td>
<td>5.4</td>
<td></td>
</tr>
<tr>
<td>Trailer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>7.5</td>
<td>10.9</td>
</tr>
<tr>
<td>2</td>
<td>7</td>
<td>12</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>5.5</td>
</tr>
<tr>
<td>4</td>
<td>5.9</td>
<td>5.8</td>
</tr>
</tbody>
</table>

### Table A5  Measured vehicle weights*

<table>
<thead>
<tr>
<th></th>
<th>2009-10-14 (empty)</th>
<th>2009-10-21 (loaded)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Truck</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Front (kg)</td>
<td>5530</td>
<td>7110</td>
</tr>
<tr>
<td>Rear (kg)</td>
<td>7920</td>
<td>16340</td>
</tr>
<tr>
<td>Total (kg)</td>
<td>13450</td>
<td>23450</td>
</tr>
<tr>
<td>Odometer (km)</td>
<td>341529</td>
<td>342548</td>
</tr>
<tr>
<td>Fuel tank (L)</td>
<td>550</td>
<td>430</td>
</tr>
<tr>
<td>Trailer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Front (kg)</td>
<td>5160</td>
<td>10010</td>
</tr>
<tr>
<td>Rear (kg)</td>
<td>5280</td>
<td>10700</td>
</tr>
<tr>
<td>Total (kg)</td>
<td>10440</td>
<td>20710</td>
</tr>
<tr>
<td>Truck+trailer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total (kg)</td>
<td>23890</td>
<td>44160</td>
</tr>
</tbody>
</table>

*At Bilprovningen in Linköping.
Tyre tread temperature and pressure

Tyre tread temperature and pressure have been measured at Däckhuset AB in Linköping as a part of the coastdown measurements.

Temperature for the tyres should be presented in parallel to ambient temperature. Data is presented on two levels:
- on a vehicle level
- on a vehicle side level. (left(l) and right(r))

In figure B1–B3 temperatures on a vehicle level are presented and in figure B4–B6 on a vehicle and side level. The figures represent different days and load conditions.

![Figure B1  Temperature conditions on a vehicle level (tyre tread) without load (14/10)](image-url)
Figure B2 Temperature conditions on a vehicle level (tyre tread) without load (21/10).

Figure B3 Temperature conditions on a vehicle level (tyre tread) with load (21/10).
Figure B4  Temperature conditions on a vehicle side level (tyre tread) without load (14/10).

Figure B5  Temperature conditions on a vehicle side level (tyre tread) without load (21/10).
Figure B6  Temperature conditions on a vehicle side level (tyre tread) with load (21/10).

Comments to figure B1–B6:

- the tyre tread temperature is approximately 9 degrees higher than ambient temperature both without and with load
- the tyre tread temperature is higher for the truck compared with the trailer both with and without load. The difference decreases with increasing load from 2 to 1 degrees C.
- the tyre tread temperature decreases during coastdown measurements
- the tyre tread temperature on the right side is higher compared to the left side.
### Table B1 Tyre pressure (bar) with load before adjustment (21/10 09.30)*

<table>
<thead>
<tr>
<th>Axle</th>
<th>Left outside</th>
<th>inside</th>
<th>Right inside</th>
<th>outside</th>
<th>Average/axle</th>
<th>Average/vehicle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Truck</td>
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<td></td>
<td>8.8</td>
<td></td>
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</tr>
<tr>
<td>1</td>
<td>8.8</td>
<td></td>
<td>7.3</td>
<td>7.6</td>
<td>7.8</td>
<td>7.5</td>
</tr>
<tr>
<td>2</td>
<td>7.8</td>
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<td></td>
<td></td>
<td>7.6</td>
</tr>
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<td>9.1</td>
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<td></td>
<td></td>
<td>9.1</td>
</tr>
<tr>
<td>Trailer</td>
<td>8.3</td>
<td></td>
<td>8.2</td>
<td></td>
<td></td>
<td>8.2</td>
</tr>
<tr>
<td>1</td>
<td>8.3</td>
<td></td>
<td>8.2</td>
<td></td>
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<td>8.3</td>
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<tr>
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<td>8.2</td>
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<td>8.1</td>
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<td>8.1</td>
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<td></td>
<td>8.4</td>
<td></td>
<td></td>
<td>8.3</td>
</tr>
</tbody>
</table>

*The tyre pressure has not been adjusted since 14/10 with one exception, the tyres on the 2nd axle on the trailer.

### Table B2 Tyre pressure (bar) with load, initial values after adjustment (21/10 10.30).

<table>
<thead>
<tr>
<th>Axle</th>
<th>Left outside</th>
<th>inside</th>
<th>Right inside</th>
<th>outside</th>
<th>Average/axle</th>
<th>Average/vehicle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Truck</td>
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<td></td>
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<td>9.0</td>
</tr>
<tr>
<td>1</td>
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<tr>
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<td>9.0</td>
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<tr>
<td>3</td>
<td>9.0</td>
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<td>9.0</td>
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<td>9.0</td>
</tr>
</tbody>
</table>
Table B3  Tyre pressure (bar) without load (21/10 15.20)*

<table>
<thead>
<tr>
<th>Axle</th>
<th>Left</th>
<th>Right</th>
<th>Average/axle</th>
<th>Average/vehicle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td>inside</td>
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<td>outside</td>
</tr>
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<td>1</td>
<td>9.5</td>
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<td>2</td>
<td>7.9</td>
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<td>8.4</td>
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<tr>
<td>3</td>
<td>9.3</td>
<td>9.3</td>
<td>9.3</td>
<td></td>
</tr>
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<td>Truck</td>
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</tr>
<tr>
<td>1</td>
<td>9.4</td>
<td>9.5</td>
<td>9.5</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>9.4</td>
<td>9.5</td>
<td>9.5</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>9.4</td>
<td>9.5</td>
<td>9.5</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>9.4</td>
<td>9.5</td>
<td>9.5</td>
<td></td>
</tr>
<tr>
<td>Trailer</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Approximately 10 km driving after unloading 20 t.
Equipment

1 Road surface quantities measured by the RST vehicle

The following statistical road characteristics are measured by the RST vehicle as an average over 20 m:

- iri, wavelength 0.25 – m, unit (mm/m)
- mpd (mean profile depth), wavelength 0.001 – 0.100 m, unit (mm)
- rut depth, unit (mm)
- crossfall, unit (%)
- curvature, unit 10000/m.

The measures for roughness are measured in both wheel tracks. mpd is measured along three different tracks. Further description of the RST system and the various measures can be found in (Arnberg et. Al, 1991) and (Vägverket, 1998).

The texture of the road is classified in different wavelength areas as follows:

- microtexture, wavelength – 0.0005 m
- macrotexture, wavelength 0.0005 – 0.050 m
- megatexture, wavelength 0.050 – 0.500 m

In this study macrotexture and roughness are used to describe the road surface.

2 Driving pattern (VBOX)

A description of the VBOX is available in (Racelogic, 2009):

“VBOX 3i is the most powerful GPS data logging system built by Racelogic. Using a new GPS engine, VBOX 3i logs data 100 times a second, and features a 400MHz power PC processor. With IMU integration, USB and Bluetooth connectivity, compact flash card logging, and audio functionality for voice tagging, VBOX 3i represents a flexible solution to a range of testing requirements.

For accurate testing even in areas where view of the sky is obstructed, VBOX 3i has the ability to take the information from a Racelogic IMU (inertial measurement unit), pictured below, and combine this with the GPS data in real time to improve the quality of the measured parameters. The three accelerometers and three gyros inside the IMU are used to keep track of the attitude of the vehicle and will greatly increase the velocity and position accuracy during periods when satellite visibility is poor.

When used with an optional DGPS Basestation, VBOX 3i is capable of achieving 40cm 95% CEP positional accuracy. This enables users to measure typical parameters during all..."
types of, acceleration, deceleration, braking, ABS and ESP testing, handling manoeuvres, and many other types of high dynamic testing.

In line with previous VBOX models, VBOX 3i is compatible with all existing peripherals including the Multifunction display, ADC03, FIM03, TC8, and Yaw rate sensor.

Non-contact 100Hz speed and distance measurement using GPS

Very low latency: 6.75ms

4 x 24bit differential analogue input channels with ±50v input range and synchronous capture

Brake/Event Trigger input of 10ns resolution.

2 x CAN Bus interface for data input & output

RS-232 serial interface

USB Interface

Bluetooth Interface

Audio voice tagging

Microphone headset included

Data logged to Compact Flash memory card

2 x 16bit User configurable analogue outputs

2 x Digital outputs

User configurable logging conditions

Logging rate selectable to 100Hz, 50Hz, 20Hz, 10Hz, 5Hz, 1Hz

Wide 7V to 30V operating range

Low current consumption

Positional accuracies of 2cm with RTK base station
Figure C1  The VBOX.
3 Weather station

Here follows a documentation of the meteorological equipment (Fine Offset Electronics)

1) Touch screen panel

2) USB port for easy connectio to your PC

3) All the weather data from the base station and weather history data with user adjustable measuring intervals can be recorded and uploaded to your PC

4) Free PC software for transfer weather data to PC

5) Rainfall data (inches or millimeters): 1-hour, 24-hour, one week, one month and total since last reset.

6) Wind chill and Dew point temperature display (°F or °C)

7) Records min. and max. wind chill and Dew point with time and date stamp

8) Wind speed (mph, m/s, km/h, knots, Beaufort)

9) Wind direction display with LCD compass

10) Weather forecast tendency arrow

11) Weather alarm modes for: a) Temperature b) Humidity c) Wind chill d) Dew point e) Rainfall f) Wind speed g) Air pressure h) Storm warning

12) Forecast icons based on changing barometric pressure

13) Barometric pressure (inHg or hPa) with 0.1hPa resolution

14) Wireless outdoor and indoor humidity (% RH)

15) Records min. and max. humidity with time and date stamp

16) Wireless outdoor and indoor temperature (°F or °C)

17) Records min. and max. temperature with time and date stamp

18) Receive and displays the radio controlled time and date (WWVB, DCF version available)

19) 12 or 24-hour time display

20) Perpetual calendar

21) Time zone setting

25 1hPa=1mbar.
22) Time alarm
23) High light LED backlight
24) Wall hanging or free standing
25) Synchronized instant reception
26) Low power consumption (over 2 years battery life for transmitter)

Set includes:
1) Receiver
2) Four outdoor sensors: thermo-hydro transmitter, wind speed sensor, wind direction sensor and rain sensor

Specifications:
1) Outdoor temperature range: -40.0 °C to + 65.0 °C (-40 °F to +149 °F)
2) Indoor temperature range: 0 °C to + 50.0 °C (32 °F to +122 °F)
3) Humidity range: 10% to 99% (1% resolution)
4) Rain volume display: 0 - 9999mm (show OFL if outside range) Resolution : 0.3mm (if rain volume < 1000mm)
1mm (if rain volume > 1000mm)
5) Wind speed: 0~100mph (show OFL if outside range)
6) Measuring range air pressure: 27.13inHg - 31.89inHg Resolution : 0.01inHg
7) Alarm duration : 120 sec
8) Transmission range up to 100m (330 feet)
9) Power consumption: a) Receiver: 3 x AA alkaline batteries (not included) b) Sensor WH7: 2 x AA alkaline batteries (not included)
10) Transmission frequency: 433MHz,868MHz(Europe) / 915MHz (North Ameria)
Description of the test route in Linghem

RST data is available for 20 m sections. The gradient is estimated for 10 m sections based on height data available at 0.1 m intervals.

**Table D1  Test route Linghem direction 1 (towards Linköping)**

<table>
<thead>
<tr>
<th></th>
<th>iri (mm/m)</th>
<th>mpd (mm)</th>
<th>Cross Fall (%)</th>
<th>Gradient (m/m)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>min</td>
<td>0.725</td>
<td>0.768</td>
<td>-4.750</td>
<td>-0.010</td>
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<tr>
<td>max</td>
<td>3.015</td>
<td>1.000</td>
<td>1.125</td>
<td>0.012</td>
</tr>
<tr>
<td>medel</td>
<td>1.238</td>
<td>0.871</td>
<td>-3.066</td>
<td>0.002</td>
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</tbody>
</table>

*10 m interval.

**Table D2  Test route Linghem direction 2 (towards Norrköping)**

<table>
<thead>
<tr>
<th></th>
<th>iri (mm/m)</th>
<th>mpd (mm)</th>
<th>Cross Fall (%)</th>
<th>Gradient (m/m)*</th>
</tr>
</thead>
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<td>min</td>
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<td>0.522</td>
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<tr>
<td>medel</td>
<td>1.187</td>
<td>0.749</td>
<td>-3.751</td>
<td>-0.002</td>
</tr>
</tbody>
</table>

*10 m interval.

The total length of the test route is 803 m.
Description of the coastdowns

Figure E1  Truck with trailer unloaded (14/10). Direction 1 (towards Linköping)

Figure E2  Truck with trailer unloaded (14/10). Direction 2 (towards Norrköping)
Figure E3  Truck without trailer, unloaded (14/10). Direction 1 (towards Linköping)

Figure E4  Truck without trailer, unloaded (14/10). Direction 2 (towards Norrköping)
Figure E5  Truck with trailer loaded (21/10). Direction 1 (towards Linköping)

Figure E6  Truck with trailer loaded (21/10). Direction 2 (towards Norrköping)
Figure E7  Truck with trailer unloaded (21/10). Direction 1 (direction towards Linköping)

Figure E8  Truck with trailer unloaded (21/10). Direction 1 (towards Linköping)
Table E1  Coastdowns for truck and trailer with no load. (2009-10-14)

<table>
<thead>
<tr>
<th>Coastdown no</th>
<th>Date</th>
<th>Speed initial (m/s)</th>
<th>Speed end (m/s)</th>
<th>dv/dt (m/s²)</th>
<th>Vehicle weight (kg)</th>
<th>T (°C)</th>
<th>Wind speed (m/s)</th>
<th>Wind dir rel (°)</th>
<th>Pressure (mbar)</th>
<th>Moisture (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>With trailer and no load</td>
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<td>1019.5</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>With trailer and no load</td>
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<td>5.7</td>
<td>105</td>
<td>1019.5</td>
<td>68</td>
</tr>
<tr>
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<td>-0.152</td>
<td>23816.8</td>
<td>4.9</td>
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<td>4.3</td>
<td>105</td>
<td>1019.5</td>
<td>71</td>
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</tbody>
</table>

Table E2  Coastdowns for truck without trailer with no load. (2009-10-14)

<table>
<thead>
<tr>
<th>Coastdown no</th>
<th>Date</th>
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<th>Speed end (m/s)</th>
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Table E3  Coastdowns for truck and trailer with load. (2009-10-21)

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<th>Wind dir rel (°)</th>
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<th>Moisture (%)</th>
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With trailer and no load |              |                     |                |              |                     |        |                 |                 |                |              |
| 21           | 2009-10-21   | 21.8                | 18.3           | -0.094       | 44230.2             | 4.2    | 0.3             | 240             | 1013.2         | 93           |
| 23           | 2009-10-21   | 14.5                | 11.3           | -0.054       | 44221.8             | 4.3    | 1.4             | 173             | 1013.2         | 94           |
| 25           | 2009-10-21   | 21.7                | 18.4           | -0.086       | 44213.4             | 4.2    | 2               | 150             | 1013.2         | 95           |
| 27           | 2009-10-21   | 14.2                | 10.8           | -0.055       | 44205.0             | 4.3    | 1.4             | 195             | 1013.2         | 95           |
| 29           | 2009-10-21   | 22.1                | 18.8           | -0.087       | 44196.6             | 4.5    | 2               | 150             | 1013.2         | 95           |
| 31           | 2009-10-21   | 14.1                | 10.8           | -0.053       | 44188.2             | 4.5    | 1.4             | 195             | 1013           | 95           |

Table E4  Coastdowns for truck and trailer with no load. (2009-10-21)

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<th>Vehicle weight (kg)</th>
<th>T (°C)</th>
<th>Wind speed (m/s)</th>
<th>Wind dir rel (°)</th>
<th>Pressure (mbar)</th>
<th>Moisture (%)</th>
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With trailer and no load |              |                     |                |              |                     |        |                 |                 |                |              |
| 33           | 2009-10-21   | 14.2                | 8.7            | -0.081       | 23780               | 5.6    | 0.7             | 105             | 1012           | 93           |
| 35           | 2009-10-21   | 21.8                | 16.5           | -0.131       | 23778               | 5.6    | 1               | 330             | 1012           | 93           |
| 37           | 2009-10-21   | 14.1                | 8.9            | -0.077       | 23775               | 5.6    | 0.7             | 105             | 1012           | 93           |
| 39           | 2009-10-21   | 22.1                | 16.7           | -0.136       | 23772               | 5.6    | 0.7             | 150             | 1012           | 94           |
| 41           | 2009-10-21   | 14.2                | 9.0            | -0.079       | 23770               | 5.7    | 0.7             | 150             | 1012           | 94           |
| 43           | 2009-10-21   | 21.4                | 16.3           | -0.123       | 23767               | 5.8    | 1               | 105             | 1012           | 94           |
### Data set for analysis

*Table F1*  Total data set truck with trailer

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*Table F2*  Reduced data set, truck with trailer (837 observations)

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VTI notat 15A-2012
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<tr>
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<td>0.056</td>
<td>0.137</td>
<td>0.678</td>
<td>0.842</td>
<td>0.891</td>
<td>-0.055</td>
<td>-0.049</td>
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<td>-</td>
<td>-</td>
<td>0.043</td>
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<td>-0.975</td>
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<td>0.004</td>
<td>-0.002</td>
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<td>0.000</td>
<td></td>
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<td>-0.008</td>
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</tr>
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<td>0.025</td>
<td>0.019</td>
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<td>m</td>
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<td>0.803</td>
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<td>-0.319</td>
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<td>0.134</td>
<td>0.510</td>
<td>0.004</td>
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<td>1</td>
<td></td>
</tr>
</tbody>
</table>

VTI notat 15A-2012
Function approaches and estimated parameters

In this Appendix estimated parameter values for different function approaches and different data sets are presented. In case of parameters not significantly different from zero italics are used.

When a reduced data set or a 1 m interval is used for analysis this is stated.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Function no.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>$trm$</td>
<td>258</td>
</tr>
<tr>
<td>$Cd$</td>
<td>.943</td>
</tr>
<tr>
<td>$Cd0$</td>
<td>.832</td>
</tr>
<tr>
<td>$Cd1$</td>
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<td>$Crz1$</td>
<td>.0000338</td>
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<tr>
<td>$Cr$</td>
<td>.00528</td>
</tr>
<tr>
<td>$Cra$</td>
<td>.00532</td>
</tr>
<tr>
<td>$Crb$</td>
<td>.00522</td>
</tr>
<tr>
<td>$Cr0$</td>
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<tr>
<td>$Cr2$</td>
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</tr>
<tr>
<td>$R^2$</td>
<td>0.76</td>
</tr>
</tbody>
</table>

*Italics if not proved different from zero (95%); bold type: input value.
### Tabel G1b: Used functions with trailer.

<table>
<thead>
<tr>
<th>No.</th>
<th>Special Description</th>
<th>Used Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cd expressed as a function of b, basic function.</td>
<td>$\frac{dv}{dt} = \left( -\frac{1}{m_{acc}} \right) \left( t_{rm} + m_1 \cdot 9.81 \cdot \sin(gr1) + m_2 \cdot 9.81 \cdot \sin(sin(gr2)) + C_d0 \cdot \left( 1 + C_d1 \cdot \sin(b) \right) \cdot f_{xl} + C_r \cdot m_1 \cdot 9.81 + C_r \cdot m_2 \cdot 9.81 \right)$.</td>
</tr>
<tr>
<td>2</td>
<td>Cd not expressed as a function of b.</td>
<td>$\frac{dv}{dt} = \left( -\frac{1}{m_{acc}} \right) \left( t_{rm} + m_1 \cdot 9.81 \cdot \sin(gr1) + m_2 \cdot 9.81 \cdot \sin(sin(gr2)) + C_d \cdot f_{xl} + C_r \cdot m_1 \cdot 9.81 + C_r \cdot m_2 \cdot 9.81 \right)$.</td>
</tr>
<tr>
<td>3</td>
<td>Cd not expressed as a function of b and use of estimated trm value as input.</td>
<td>$\frac{dv}{dt} = \left( -\frac{1}{m_{acc}} \right) \left( 260 + m_1 \cdot 9.81 \cdot \sin(gr1) + m_2 \cdot 9.81 \cdot \sin(sin(gr2)) + C_d \cdot f_{xl} + C_r \cdot m_1 \cdot 9.81 + C_r \cdot m_2 \cdot 9.81 \right)$.</td>
</tr>
<tr>
<td>4</td>
<td>Separate rolling resistance parameters for the truck and for the trailer and use of estimated trm value as input.</td>
<td>$\frac{dv}{dt} = \left( -\frac{1}{m_{acc}} \right) \left( 260 + m_1 \cdot 9.81 \cdot \sin(gr1) + m_2 \cdot 9.81 \cdot \sin(sin(gr2)) + C_d0 \cdot \left( 1 + C_d1 \cdot \sin(b) \right) \cdot f_{xl} + C_r \cdot m_1 \cdot 9.81 + C_r \cdot m_2 \cdot 9.81 \right)$.</td>
</tr>
<tr>
<td>5</td>
<td>Test of Cr being a function of vehicle speed and use of estimated trm value as input.</td>
<td>$\frac{dv}{dt} = \left( -\frac{1}{m_{acc}} \right) \left( 260 + m_1 \cdot 9.81 \cdot \sin(gr1) + m_2 \cdot 9.81 \cdot \sin(sin(gr2)) + C_d0 \cdot \left( 1 + C_d1 \cdot \sin(b) \right) \cdot f_{xl} + \left( m_1 + m_2 \right) \cdot 9.81 \cdot \left( C_{ra} + C_{rb} \cdot V \right) \right)$.</td>
</tr>
<tr>
<td>6</td>
<td>Test of Cr being a function of wheel load and use of estimated trm value as input.</td>
<td>$\frac{dv}{dt} = \left( -\frac{1}{m_{acc}} \right) \left( 260 + m_1 \cdot 9.81 \cdot \sin(gr1) + m_2 \cdot 9.81 \cdot \sin(sin(gr2)) + C_d0 \cdot \left( 1 + C_d1 \cdot \sin(b) \right) \cdot f_{xl} + \left( m_1 + m_2 \right) \cdot 9.81 \cdot \left( C_{ra} + C_{rb} \cdot \left( 1 + C_{rb} \cdot V \right) \right) \right)$.</td>
</tr>
<tr>
<td>7</td>
<td>Test of Cr being a function of wheel relative load and use of estimated trm value as input.</td>
<td>$\frac{dv}{dt} = \left( -\frac{1}{m_{acc}} \right) \left( 260 + m_1 \cdot 9.81 \cdot \sin(gr1) + m_2 \cdot 9.81 \cdot \sin(sin(gr2)) + C_d0 \cdot \left( 1 + C_d1 \cdot \sin(b) \right) \cdot f_{xl} + \left( m_1 + m_2 \right) \cdot 9.81 \cdot \left( C_{ra} + C_{rb} \cdot \left( 1 + C_{rb} \cdot T \right) \right) \right)$.</td>
</tr>
<tr>
<td>8</td>
<td>Test of Cr being a function of ambient temperature and use of estimated trm value as input.</td>
<td>$\frac{dv}{dt} = \left( -\frac{1}{m_{acc}} \right) \left( 260 + m_1 \cdot 9.81 \cdot \sin(gr1) + m_2 \cdot 9.81 \cdot \sin(sin(gr2)) + C_d0 \cdot \left( 1 + C_d1 \cdot \sin(b) \right) \cdot f_{xl} + \left( m_1 + m_2 \right) \cdot 9.81 \cdot \left( C_{ra} \cdot (1 + C_{rb} \cdot T) \right) \right)$.</td>
</tr>
<tr>
<td>9</td>
<td>Test of Cr being a function of iri and mpd and use of estimated trm as input.</td>
<td>$\frac{dv}{dt} = \left( -\frac{1}{m_{acc}} \right) \left( 260 + m_1 \cdot 9.81 \cdot \sin(gr1) + m_2 \cdot 9.81 \cdot \sin(sin(gr2)) + C_d0 \cdot \left( 1 + C_d1 \cdot \sin(b) \right) \cdot f_{xl} + \left( m_1 + m_2 \right) \cdot 9.81 \cdot \left( C_{ra} + C_{rb} \cdot (1 + C_{rb} \cdot T) \right) \right)$.</td>
</tr>
</tbody>
</table>
### Tabell G2a  Estimated parameter values with trailer, reduced data set.*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Function no.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>trm</td>
<td></td>
<td>293</td>
<td>666</td>
<td>260</td>
<td></td>
</tr>
<tr>
<td>Cd0</td>
<td>.815</td>
<td>.637</td>
<td>.703</td>
<td>.668</td>
<td></td>
</tr>
<tr>
<td>Cd1</td>
<td>1.78</td>
<td>2.350</td>
<td>2.24</td>
<td>2.23</td>
<td></td>
</tr>
<tr>
<td>Cr0</td>
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<td>.00347</td>
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<td></td>
<td></td>
</tr>
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<td>Cr10</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cr11</td>
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<td>.000169</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cr11e</td>
<td>-.0939</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>.000659</td>
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<td>Cr</td>
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<td>Crb</td>
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<td>R²</td>
<td>.711</td>
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<td>.718</td>
<td>.719</td>
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</tr>
</tbody>
</table>

*Italics if not proved different from zero (95%); bold type: input value.

### Tabell G2b  Used functions with trailer, reduced data set.

<table>
<thead>
<tr>
<th>No.</th>
<th>Special</th>
<th>Used function</th>
</tr>
</thead>
</table>
| 1   | *Cd* expressed as a function of *b*, basic function. | \[
\frac{dv}{dt} = \frac{-1}{macc} \cdot (trm + m1 \cdot 9.81 \cdot \sin(gr1) + m2 \cdot 9.81 \cdot \sin(gr2) + Cd0 \cdot (1 + Cd1 \cdot \sin(b)) \cdot fxl + Cr \cdot m1 + Cr \cdot m2).\]
| 2   | Test of *Cr* being a function of vehicle speed | \[
\frac{dv}{dt} = \frac{-1}{macc} \cdot (trm + m1 \cdot 9.81 \cdot \sin(gr1) + m2 \cdot 9.81 \cdot \sin(gr2) + Cd0 \cdot (1 + Cd1 \cdot \sin(b)) \cdot fxl + (Cra + Crb \cdot V) \cdot m1 + (Cra + Crb \cdot V) \cdot m2).\]
| 3   | Test of *Cr* being a function of *iri* and *mpd* and use of estimated *trm* value as input | \[
\frac{dv}{dt} = \frac{-1}{macc} \cdot (260 + m1 \cdot 9.81 \cdot \sin(gr1) + m2 \cdot 9.81 \cdot \sin(gr2) + Cd0 \cdot (1 + Cd1 \cdot \sin(b)) \cdot fxl + m1 \cdot (Cr0 + Cr11 \cdot V \cdot iri1 + Cr20 \cdot mpd1) + m2 \cdot (Cr0 + Cr11 \cdot V \cdot iri2 + Cr20 \cdot mpd2)).\]
| 4   | Test of *Cr* being a function of *iri* and *mpd* extended with a mass related exponent on speed in the roughness term and use of estimated *trm* value as input. | \[
\frac{dv}{dt} = \frac{-1}{macc} \cdot (260 + m1 \cdot 9.81 \cdot \sin(gr1) + m2 \cdot 9.81 \cdot \sin(gr2) + cl012 \cdot (1 + cl112 \cdot \sin(brad)) \cdot fxl + m1 \cdot (Cr0 + Cr11 \cdot (V^{**} (1 + Cr11e \cdot m1 / 10000)) \cdot iri1 + Cr20 \cdot mpd1) + m2 \cdot (Cr0 + Cr11 \cdot (V^{**} (1 + Cr11e \cdot m2 / 10000)) \cdot iri2 + Cr20 \cdot mpd2)).\]
### Table G3a Estimated parameter values with and without trailer.*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Function no.</th>
<th>1 (14/10 without)</th>
<th>2 (14/10 with)</th>
<th>3 (21/10 with)</th>
<th>4 (21/10 with)</th>
</tr>
</thead>
<tbody>
<tr>
<td>trm</td>
<td></td>
<td>260</td>
<td>260</td>
<td>225</td>
<td>260</td>
</tr>
<tr>
<td>Cd</td>
<td></td>
<td>0.740173</td>
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<td>.875</td>
<td>.871</td>
</tr>
<tr>
<td>Cr</td>
<td></td>
<td>.004131</td>
<td>.00690</td>
<td>.00546</td>
<td>.00538</td>
</tr>
<tr>
<td>R²</td>
<td></td>
<td>0.711</td>
<td>0.665</td>
<td>0.762</td>
<td>0.762</td>
</tr>
</tbody>
</table>

*Italics if not proved different from zero (95%); bold type: input value.

### Table G3b Used functions with and without trailer.

<table>
<thead>
<tr>
<th>No.</th>
<th>Special</th>
<th>Used function</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14/10 without trailer. No adjustment for meteorological wind. trm=260.</td>
<td>$\frac{dv}{dt} = \left(\frac{1}{macc}\right) \times (260 + m1 \times 9.81 \times \sin(\text{gr1}) + m2 \times 9.81 \times \sin(\text{gr2}) + \text{Cd} \times f(\text{xl}) + \text{cr0} \times m1 \times 9.81 \times m2 \times 9.81)$.</td>
</tr>
<tr>
<td>2</td>
<td>14/10 with trailer. No adjustment for meteorological wind. trm=260.</td>
<td>$\frac{dv}{dt} = \left(\frac{1}{macc}\right) \times (260 + m1 \times 9.81 \times \sin(\text{gr1}) + m2 \times 9.81 \times \sin(\text{gr2}) + \text{Cd} \times f(\text{xl}) + \text{cr0} \times m1 \times 9.81 \times m2 \times 9.81)$.</td>
</tr>
<tr>
<td>3</td>
<td>21/10 with trailer. No adjustment for meteorological wind.</td>
<td>$\frac{dv}{dt} = \left(\frac{1}{macc}\right) \times (\text{trm} + m1 \times 9.81 \times \sin(\text{gr1}) + m2 \times 9.81 \times \sin(\text{gr2}) + \text{Cd} \times f(\text{xl}) + \text{cr0} \times m1 \times 9.81 \times m2 \times 9.81)$.</td>
</tr>
<tr>
<td>4</td>
<td>21/10 with trailer. No adjustment for meteorological wind. trm=260.</td>
<td>$\frac{dv}{dt} = \left(\frac{1}{macc}\right) \times (260 + m1 \times 9.81 \times \sin(\text{gr1}) + m2 \times 9.81 \times \sin(\text{gr2}) + \text{Cd} \times f(\text{xl}) + \text{cr0} \times m1 \times 9.81 \times m2 \times 9.81)$.</td>
</tr>
</tbody>
</table>

### Table G4a Estimated parameter values with trailer (1m).*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Function no.</th>
</tr>
</thead>
<tbody>
<tr>
<td>trm</td>
<td>249</td>
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<tr>
<td>Cd0</td>
<td>.838</td>
</tr>
<tr>
<td>Cd1</td>
<td>1.71</td>
</tr>
<tr>
<td>Cr</td>
<td>.00528</td>
</tr>
<tr>
<td>R²</td>
<td>0.062</td>
</tr>
</tbody>
</table>

*Italics if not proved different from zero (95%).
### Table G4b: Used function with trailer (1 m).

<table>
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<tr>
<th>No.</th>
<th>Special</th>
<th>Used function</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1  Cd expressed as a function of b, basic function.</td>
<td>(\frac{dv}{dt} = \left(-\frac{1}{macc}\right) \times (trm + \sin(gr1)^{} \times m1^{} \times 9.81^{} + \sin(gr2)^{} \times m2^{} \times 9.81^{} + (m1^{} + m2^{}) \times 9.81^{} \times Cr^{} + Cd0^{} \times (1^{} + Cd1^{} \times \sin(b))^{} \times fxl))</td>
</tr>
</tbody>
</table>
Examples on the use of the estimated function

**Table H.1** Estimated parameter values for truck with trailer.* (A)

<table>
<thead>
<tr>
<th>trm</th>
<th>Cr</th>
<th>Cd0</th>
<th>Cd1</th>
</tr>
</thead>
<tbody>
<tr>
<td>258</td>
<td>0.00528</td>
<td>0.832</td>
<td>1.73</td>
</tr>
</tbody>
</table>

\[ \frac{\text{dv/dt}}{\text{macc}} = -(trm + m_1 \cdot g_1 + m_2 \cdot g_2 + (m_1 + m_2) \cdot Cr + Cd0 \cdot (1 + Cd1 \cdot \sin(b)) \cdot fxl)/macc; \]
\[ fxl = dnl \cdot Ayz \cdot \cos(b) \cdot vlr^2/2 \]

**Table H.2** Angle \( (b \ \text{rad}) \) between resulting wind and the x-axle of the vehicle.
Meteorological wind speed: 2.5 m/s.

<table>
<thead>
<tr>
<th>V (m/s)</th>
<th>a (rad)</th>
<th>2.5</th>
<th>5</th>
<th>7.5</th>
<th>10</th>
<th>12.5</th>
<th>15</th>
<th>17.5</th>
<th>20</th>
<th>22.5</th>
<th>25</th>
<th>27.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.5</td>
<td>0.25</td>
<td>0.17</td>
<td>0.12</td>
<td>0.10</td>
<td>0.08</td>
<td>0.07</td>
<td>0.06</td>
<td>0.05</td>
<td>0.05</td>
<td>0.04</td>
<td>0.04</td>
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<tr>
<td>1</td>
<td>0.50</td>
<td>0.32</td>
<td>0.23</td>
<td>0.18</td>
<td>0.15</td>
<td>0.13</td>
<td>0.11</td>
<td>0.10</td>
<td>0.09</td>
<td>0.08</td>
<td>0.07</td>
<td></td>
</tr>
<tr>
<td>1.5</td>
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<td>0.45</td>
<td>0.31</td>
<td>0.24</td>
<td>0.19</td>
<td>0.16</td>
<td>0.14</td>
<td>0.12</td>
<td>0.11</td>
<td>0.10</td>
<td>0.09</td>
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</tr>
<tr>
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<td>1.00</td>
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<td>0.34</td>
<td>0.25</td>
<td>0.20</td>
<td>0.16</td>
<td>0.14</td>
<td>0.12</td>
<td>0.11</td>
<td>0.09</td>
<td>0.09</td>
<td></td>
</tr>
<tr>
<td>2.5</td>
<td>1.25</td>
<td>0.46</td>
<td>0.27</td>
<td>0.18</td>
<td>0.14</td>
<td>0.11</td>
<td>0.10</td>
<td>0.08</td>
<td>0.07</td>
<td>0.06</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1.50</td>
<td>0.14</td>
<td>0.07</td>
<td>0.05</td>
<td>0.04</td>
<td>0.03</td>
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**Table H.3** Angle \( (b \ \text{rad}) \) between resulting wind and the x-axle of the vehicle.
Meteorological wind speed: 5 m/s.

<table>
<thead>
<tr>
<th>V (m/s)</th>
<th>a (rad)</th>
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Table H4  Driving resistance Fx (N) at a meteorological wind speed of 2.5 (m/s) and \( l_f = 50\% \).

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<th>10</th>
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<th>15</th>
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Table H.5  Driving resistance Fx (N) at a meteorological wind speed of 5 (m/s) and \( l_f = 50\% \).

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VTI är ett oberoende och internationellt framstående forskningsinstitut som arbetar med forskning och utveckling inom transportsektorn. Vi arbetar med samtliga trafikslag och kärnkompetensen finns inom områdena säkerhet, ekonomi, miljö, trafik- och transportanalys, beteende och samspelet mellan människa-fordon-transportsystem samt inom vägkonstruktion, drift och underhåll. VTI är världsklass inom ett flertal områden, till exempel simulatorteknik. VTI har tjänster som sträcker sig från förstudier, oberoende kvalificerade utredningar och expertutlåtanden till projektledning samt forskning och utveckling. Vår tekniska utrustning består bland annat av körsimulatorer för väg- och järnvägstrafik, väglaboratorium, däckprovningsanläggning, krockbanor och mycket mer. Vi kan även erbjuda ett brett utbud av kurser och seminarier inom transportområdet.

VTI is an independent, internationally outstanding research institute which is engaged on research and development in the transport sector. Our work covers all modes, and our core competence is in the fields of safety, economy, environment, traffic and transport analysis, behaviour and the man-vehicle-transport system interaction, and in road design, operation and maintenance. VTI is a world leader in several areas, for instance in simulator technology. VTI provides services ranging from preliminary studies, highlevel independent investigations and expert statements to project management, research and development. Our technical equipment includes driving simulators for road and rail traffic, a road laboratory, a tyre testing facility, crash tracks and a lot more. We can also offer a broad selection of courses and seminars in the field of transport.