DRIVING RESISTANCE FROM RAILROAD TRAINS

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This report methods and parameters for calculating the driving resistance of railroad trains. Calculations and comparisons are presented for aerodynamic, rolling and total resistance for a variety of freight trains under different loading conditions, operating speed and configuration. Simplified methods are presented for the estimation of the driving resistance for passenger trains. This report is a supplement to the ARTEMIS rail emissions model.</td></tr>
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1. Introduction

The physical configuration of a train has an impact on its performance. Wagon size, arrangement etc. affect especially the aerodynamic resistance, which in turn affects power requirements and air pollutant emissions. In this report, the effects of wagon type, arrangement and loading are investigated. Knowledge of the effect of train configuration on energy consumption can be used to examine the effects of train arrangements on energy consumption and emissions.

Through the methods collected and illustrated in this report, it should be possible to make a reasonable estimate of the driving resistance parameters for most kinds of trains encountered in operation. This combined with a detailed technical model and knowledge of driving operations can then be used to perform accurate, technically based estimated of train energy consumption and eventually air pollutant emissions.

The results here are intended to be a background source for determining values to be used in the ARTEMIS rail energy consumption and emissions model. The model allows calculation of an individual train, and a specific, used defined driving cycle. The data here can be used to define driving resistance characteristics for a single train, or to estimate appropriate average values for fleet calculations.

2 Basic concepts

The following is an introduction to the analysis of a driving pattern.
The report is based on the analysis of a freight train, but the methods used can also be applied to passenger trains, and the necessary values are given as well as those for freight trains.

2.1 Driving resistance

Figure 1 is a sketch of the resistance that affects the motion of a freight train.

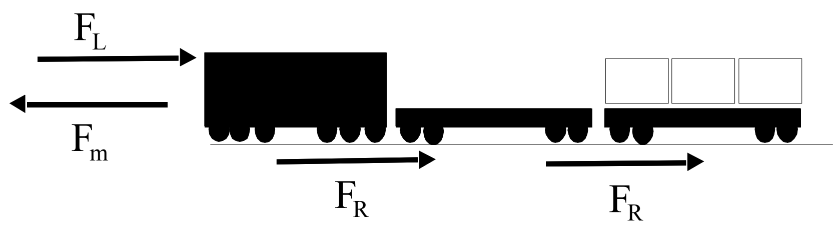


Figure 2.1

The two most important resistances are the air resistance, F_L and the rolling resistance F_R. The air resistance comes from pressure forces arising when the air in front of the train is set in motion by the train. Rolling resistance arises due to friction between the wheel and the tracks. Inelastic wheel deformation can give rise to rolling resistance in vehicles with tires, but in not important with trains.
The locomotive engine overcomes these resistances. This is best illustrated by writing Newton's 2. law in the direction of the load:

$$\begin{aligned} N2 \leftarrow: \quad & m \cdot a = F_M - (F_R + F_L) \Leftrightarrow \\ & m \cdot a = F_M - F_R - F_L \end{aligned} \qquad (2.1)$$

Where : m is the total mass of the train in [kg]
a is the train acceleration in [m/s^2]
F_M is the tractive force delivered by the locomotive in [N]
F_R and F_L are the rolling and air resistances in [N]

For operation with constant speed, the acceleration a = 0 which gives:

$$\begin{aligned} N2 \leftarrow: \quad & m \cdot 0 = F_M - (F_R + F_L) \Leftrightarrow \\ & F_M = F_R + F_L \end{aligned} \qquad (2.2)$$

In the case where the tractive force is greater than the sum of the rolling resistance and the air resistance, the train can accelerate, or climb a grade.

2.2 Energy consumption

The power of the locomotive can be calculated from a knowledge of the driving resistance of the train. For a train with total driving resistance F and speed *v,* the total power consumption from motion, P, is given by:

$$P = v \cdot F \qquad (2.3)$$

That is, for constant speed, the required power is proportional to the total driving resistance. This is the power at the wheels of the locomotive. The drive train efficiency must be considered to obtain the final energy consumption.

3 Calculation of air resistance

3.1 Calculation method

The purpose of this section is to describe the air resistance of a freight train. The air resistance is a function of the train area, form and speed, according to the following equation (1):

$$F_L = \frac{\rho}{2} \cdot c_L \cdot A_{Norm} \cdot v^2 \qquad (3.1)$$

Where:

F_L is the total air resistance
A_{Norm} is the normal-frontal area in m^2 (A_{Norm} assumed 10 m^2)
v in the train speed in m/s
ρ is the air density inkg/m^3
c_L is the drag coefficient (dimensionless)

The coefficient c_L given for in Equation 3.1 is for the entire train. It is possible to divide c_L, so that the individual coefficient can be calculated for the individual portions of the train.
The value of c_L is calculated from the contributions from the locomotive and the string of cars:

$$c_{L,tot} = c_{L,lok} + \sum c_{L,v} \qquad (3.2)$$

Where: $c_{L,.tot}$ is the air resistance coefficient for the entire train.
$c_{L,lok}$ is the air resistance coefficient for the locomotive.
$c_{L,v}$ is the air resistance coefficient for the following string of cars as a unit.

In the calculation of $c_{L,v}$, the first and last wagons are calculated separately from the rest of the string of cars. This is because the air resistance for these wagons is larger than that for the wagons in the middle. The values of c_L have been measured and depend on the specific locomotive/wagon. Table 3.2 lists values for different locomotives (1).
It should be noted, that the values in the tables are given such that extra contributions for the first and last wagons are included with the locomotive. When using the values in the tables, all the wagons can be assumed to be intermediate wagons.

The equation above is for the calculation of homogeneous wagon strings. This limits the validity, though such trains are seen for goods transport. This is not a problem for passenger trains, where a non-homogeneous wagon string would be an exception. Goods trains can, however be very inhomogeneous, and so a modification of Equation 3.2 is necessary.

The principle in the redefinition is to take the c_L- value for the wagon in question, and add a contribution for the extra area that will give extra air resistance. As an example, two goods wagons can be mentioned - a flat and a high. If the high wagon is coupled in front of the low, there will not be any extra area, and the air resistance coefficient can therefore be calculated normally. On the other hand, if the low wagon is coupled in front of the high, a portion of the high goods wagon's frontal area will not be covered by the flat wagon. The non-covered area there gives rise to extra air resistance and must be included. In the calculation of the total $c_{L,v}$ for the two wagons, the two $c_{L,m}$-values are added together, since a contribution for that portion of the frontal area which is not covered by the flat must be included. The contribution consists of a value c_{Lf} as well as a portion α for the increase in the frontal area. That is to say:

$$c_{L,tot} = \sum c_{L,m} + \alpha \cdot c_{L,f} \tag{3.3}$$

where: $c_{L,tot}$ is the total air resistance coefficient.
$c_{L.m}$ is the air resistance coefficient for a wagon in the middle of the train
$c_{L,F}$ is the air resistance coefficient for the wagon as in the front of the train
α is an area ratio that is obtained when a wagon is followed by another wagon with greater frontal area.

3.2 Sample Calculation

A wagon with a frontal area of 7 m^2 is followed by a wagon with a frontal area of 10 m^2. The first wagon has a $c_{L,m}$ of 0,236. For the following, $c_{L.m}$ = 0,159 and $c_{L,F}$ = 0,697. Then α is calculated as: (10-7)/10 = 0,3. From Equation 6, the total value of $c_{L,tot}$ becomes:

$$c_{L,tot} = 0{,}236 + 0{,}159 + 0{,}3 \cdot 0{,}697 = 0{,}6041$$

It can be seen that the total air resistance coefficient becomes considerably larger than for each of the wagons individually, which was only 0,236+0,159 = 0,395. In the example, $c_{L,tot}$ increased by about 50%.

<u>3.3 Data</u>

Table 3.1 Constants for the calculation of aerodynamic resistance from locomotives (1).

Electric locomotives	**Air Resistance Coefficient $c_{L,lok}$**
- Four axles, normal shape	0,80
- Four axles aerodynamic shape	0,45
- Six axles, normal shape	1,10
- Six axles aerodynamic shape	0,55
- BR 103	0,50
- BR 112	0,54
- BR 110	0,61
Diesel locomotives	
- Four axle	0,60
- Six axles	1,10
- Middle axles	1,00

For wagons, the values in tables 3.2 and 3.3 can be used:

Table 3.2: Constants for the calculation of aerodynamic resistance from passenger wagons (1).

Passenger cars	**Air Resistance Coefficient $c_{L,v}$**
General	0,15
26,4 m (Standard German passenger wagon)	0,11

For operation with non-homogeneous wagon strings, that is with wagons of different heights, cL,v for the train is not equal to $c_{L,M}$ times the number of wagons.
Since all wagons do not have the same height, and therefore, not the same frontal areal, the wagon string cannot be calculated as a coherent unit..

Table 3.3: Constants for the calculation of aerodynamic resistance from freight wagons (1).

Goods Wagons	$c_{L,M}$	$c_{L,f}$
Gls 205 Closed doors	0,092	0,900
Gls 205 Open doors	0,100	0,967
ES 040 empty, open	0,249	0,679
ES 040 loaded	0,119	0,673
Ed 090 empty, open	0,178	0,76
Ed 090 loaded	0,043	0,844
Fad 168 empty, open	0,228	1,081
Fad 168 loaded	0,115	0,983
Eaos 106 empty, open	0,409	0,730
Eaos 106 loaded	0,141	0,769
Kbs 442:		
-empty, without stakes	0,116	0,496
- empty, with stakes	0,159	0,697
-loaded with, 2 - 20 foot containers	0,153	0,715
Sgis 716:		
--empty, without stakes	0,165	0,601
--empty, with stakes	0,236	0,686
-loaded 1 - 20 foot container in middle	0,452	0,885
-loaded 2 - 20foot container in middle	0,276	0,850
-loaded 1 - 20 foot container in each end.	0,392	0,866
-loaded 3- 20 foot containers	0,218	0,866

The different α-values for random arrangements are shown in Appendix 2.

4 Air resistance as a function of speed - homogeneous train strings

The following shows the significance of loading on the air resistance of a train and the shape of the wagon string. The train types are the same for the individual graphs, that is, 1 diesel locomotive plus 20 wagons of a give type. A summary of the different wagons and there technical specifications is found in Appendix 1.

4.1 Bulk carrier wagons

The first train is a train for the transport of gravel, stones, *etc*. with special cars for that purpose. The train consists of a diesel locomotive and 20 Fad-wagons. The air resistance force is shown as a function of speed in Figure 4.1 for an empty train and a loaded train

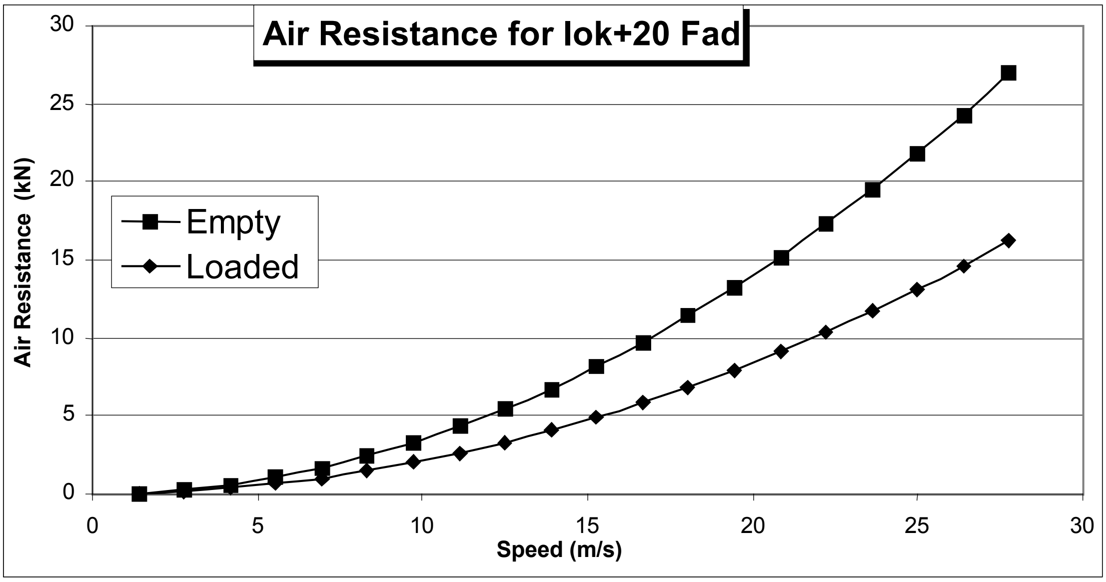


Figure 4.1 Air resistance as a function of speed and loading for bulk carrier type wagons.

Figure 4.1 shows that the air resistance for the fully loaded train is about 43% lower than that of the empty train. This is mainly because the wagons are not covered. Therefore, there is a turbulent circulation of air in the empty wagons, which results in a greater air resistance for the empty train.

To calculate the total resistance, the rolling resistance must be included as well. Since this is proportional to the weight of the train, the difference in the final results for the two conditions will be moderated. This situation will be investigated later in the report.

4.2 Open Goods Wagons

The next wagon type is an open wagon. That is, a flat car. The question is, how much does the air resistance depend on whether the wagon is empty or loaded.

The first wagon types are litra Ed and ES. Both wagons are two-axle open wagons with high sides. There are certain differences that give different C_v-values. The air resistance for a train with 20 Ed/Es is shown in Figure 4.2.

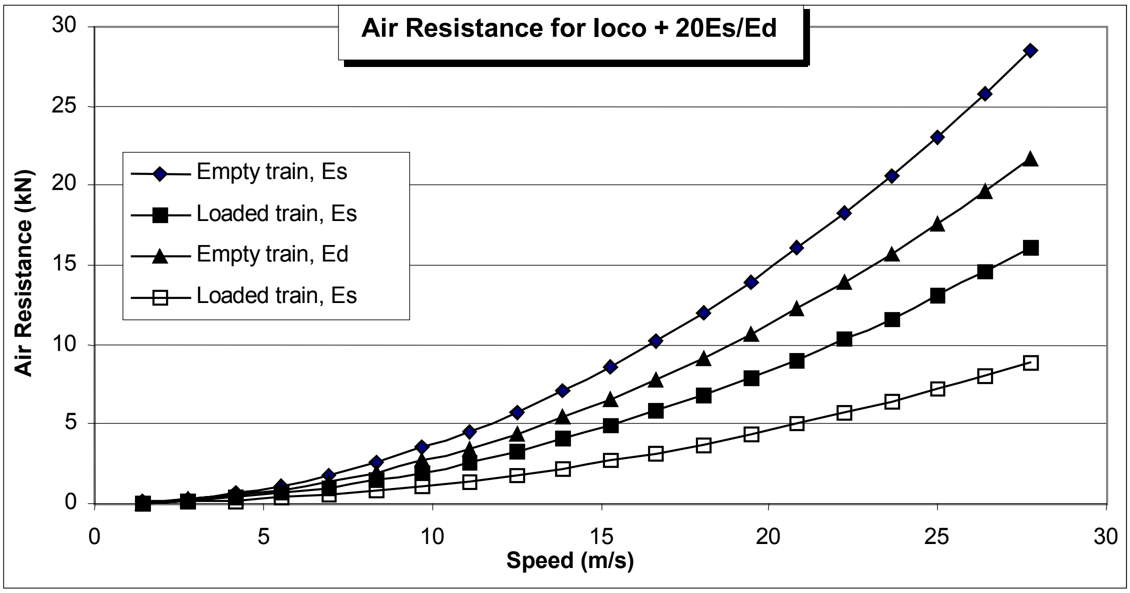


Figure 4.2 Air resistance as a function of speed and loading for open goods wagons.

As expected, Figure 4.2 shows that the empty train strings give rise to the greatest air resistance. For the Es wagon, the difference is about 43 %, while for the Ed wagon the difference is about. 59 %. The reasons for the differences between the ES and Ed wagons are not clear.

The next wagon is an open goods wagon, a four-axle type Eaos. The wagon is longer (14,04m) and has a greater capacity (58,0 t). The air resistance is shown in Figure 4.3.

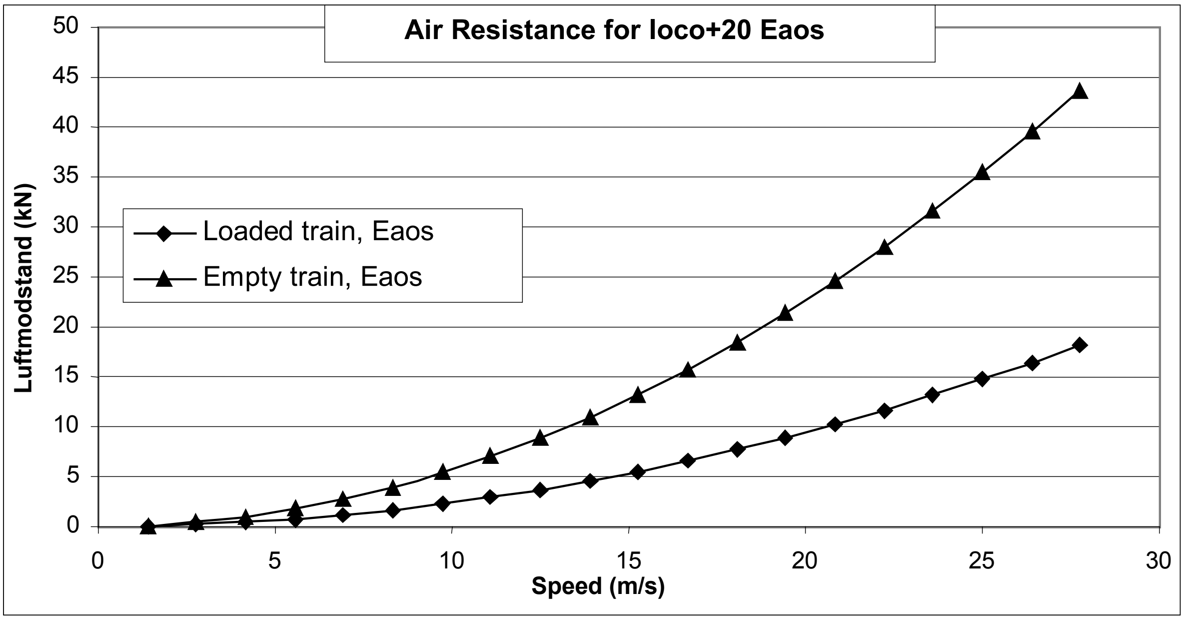


Figure 4.3 Air resistance as a function of speed and load for a four-axle open goods wagon.

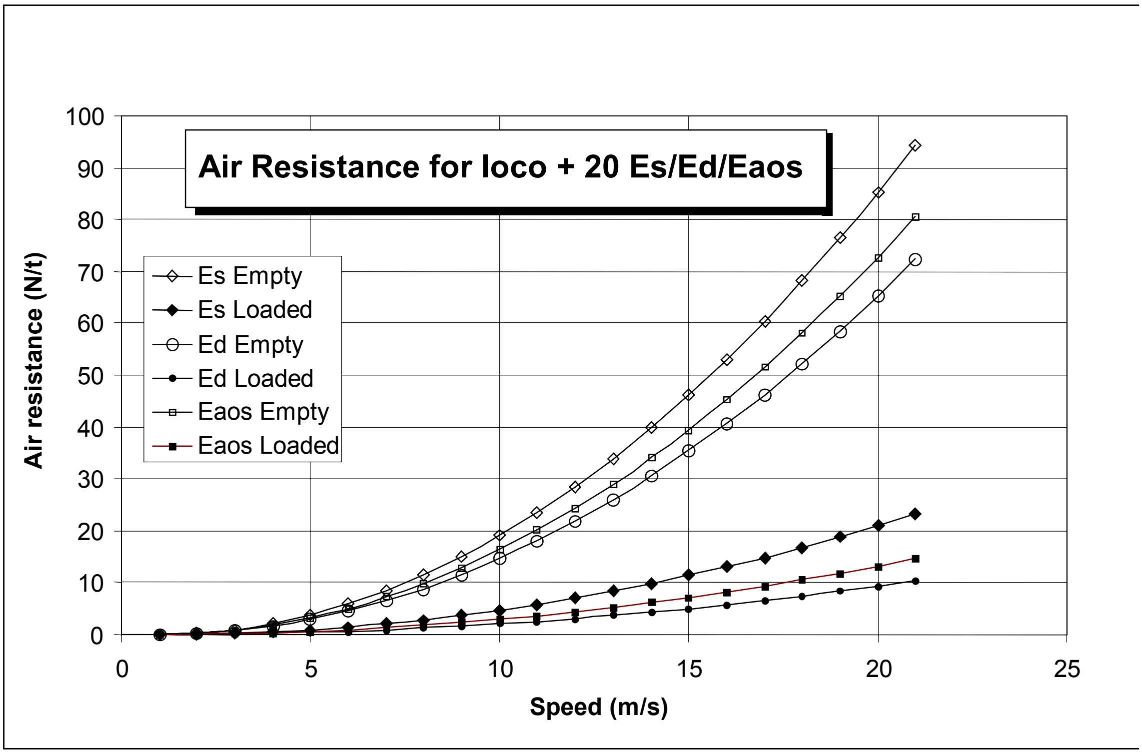


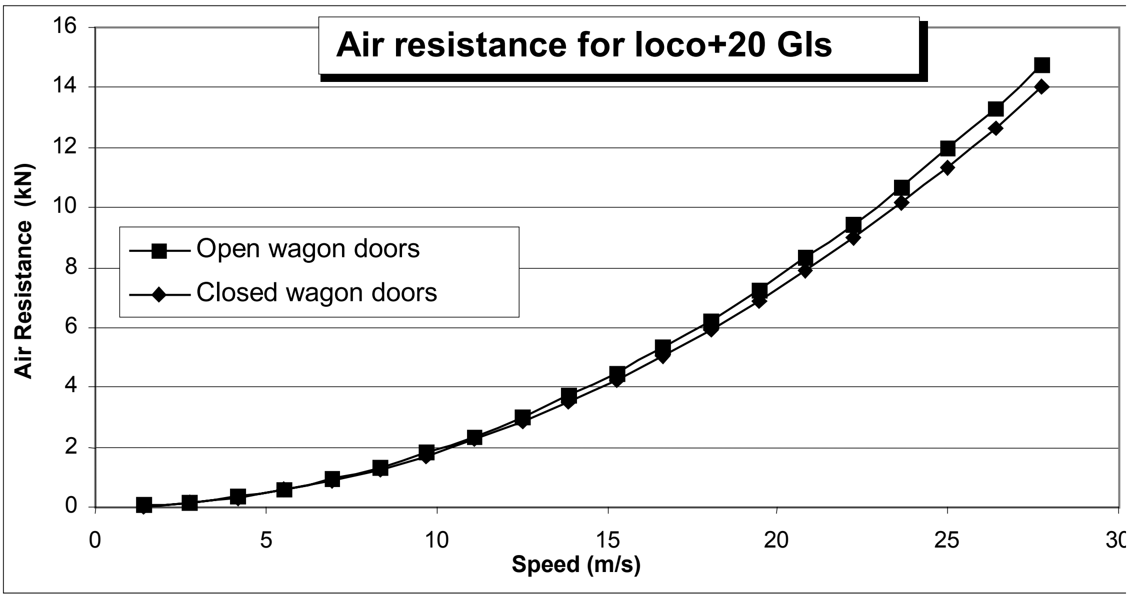
Figure 4.4 Weight specific air resistance as a function of speed and load for a four-axle open goods wagon and 2 two-axle goods wagons

In this case as well, the empty wagon gives the greatest air resistance. The difference in air resistance between the empty and loaded trains is about 58%.

In order to compare the three wagon types, the air resistance per ton is shown in Figure 4.4. The trains lie in two groups, depending on whether they are loaded or not. The empty trains have a high specific air resistance due to a higher air resistance coefficient and particularly because the air resistance is divided by a low weight value. Similarly, for the loaded trains, the specific air resistance is lower, primarily due to the high value of the weight..

4.3 Closed Wagons

The next type of goods wagon considered is the closed type. Since these wagons have covered tops, the load only affects the rolling resistance. When looking at air resistance then, it is not of interest whether the wagon is loaded or not. On the other hand, it may be worth considering whether the doors are open or closed. The difference is shown in Figure 4.5



Figur 4.5 Air resistance as a function of speed for a two-axle closed goods wagon with open and closed doors.

There is not much effect of door opening/closing, only about 5%. For larger wagons with a greater number of doors, the difference could be larger, but is much less than other factors. Operation with open doors is not common in European rail transport.

4.4 Flat cars

The last type of wagon is a flat car. This type of wagon is used to transport large irregularly shaped articles, and not the least, containers. Two types are considered, first the two-axle Kbs and then the four axle Sgis. Different cases case be discussed for each usage.

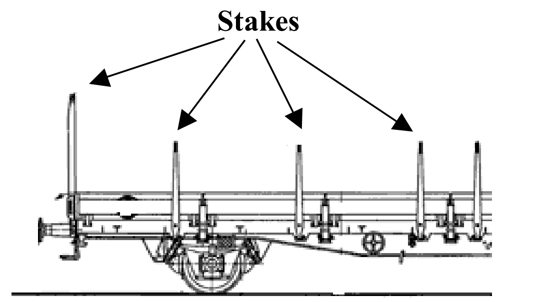


Figure 4.6 Stakes on a flat car

The first is a general empty wagon. Then one can consider an empty wagon with stakes on the sides as shown in Figure 4.6. The stakes are set up on the sides of the wagons to attach tarpaulins for covering, and chains for load securing.

Effect of stakes

A loaded wagon can be loaded in many ways. However, only values for loading with containers have been found, so the analysis will be limited to this type of loading. On the other hand, it is possible to load a flat car with containers in different ways. There are container of 20, 30 and 40-foot lengths. In addition, a wagon can hold up to three 20-foot containers per wagon, which can be arranged in different order. The first case is the two-axle type kbs. Figure 4.7 shows the air resistance for an empty train with and with out stakes+/- and a container.

Figure 4.7 shows that there is no significant difference for an empty wagon whether the stakes are in place or if it is loaded with a container (no stakes), the difference being on the order of about 3%. The air resistance for the empty train without the stakes in position is about 20% lower than with the stakes in place for an empty wagon.

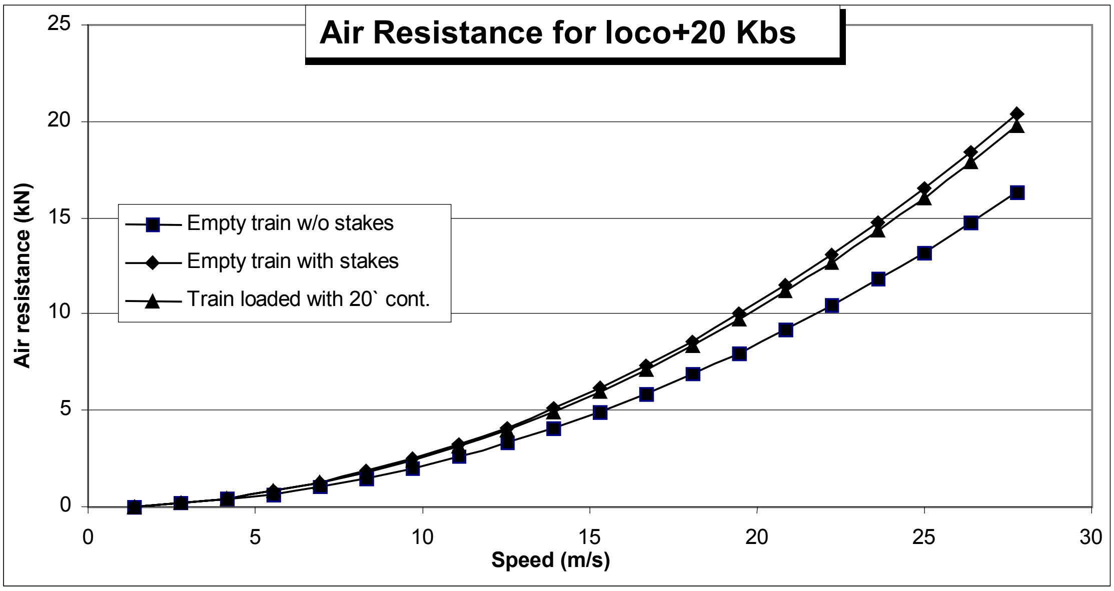


Figure 4.7 Air resistance as a function of speed and load for a goods train with two-axle flat cars.

The next wagon is the four-axle type Sgis. In contrast to the kbs, that can only load two 20' containers, the litra Sgis can accommodate three. That is, the Sgis can have a load of 62 ton, while the kbs can only have a load of 27,5 ton. Figure 4.8 shows the air resistance.

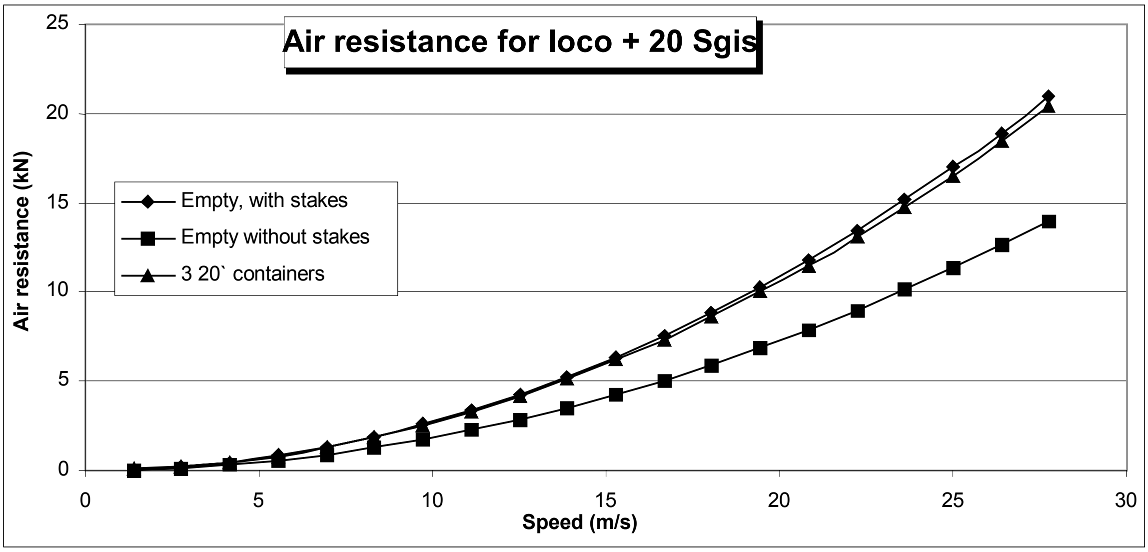


Figure 4.8 Air resistance as a function of speed and load for a goods train with four-axle flat cars.

Just as for the for kbs there is a difference if the stakes are up or down. The difference is about 24%, which is more than for the kbs wagon. This could be because the Kbs wagon has more and taller stakes than the Sgis wagon. On the other hand, the kbs has low wagon sides that can be raised or lowered like sideboards, while the Sgis is completely flat. Therefore the stakes will have a greater effect on the air resistance of the Sgis.

In general, the above figures show that upright stakes give an increase in air resistance of the same magnitude and a wagon fully loaded with containers. This is most likely due to flow resistance and turbulence around the stakes.

4.5 The effect of Container Loading Arrangement

Since it is longer, and has several possibilities for load arrangement, four loading cases are shown for the Sgis wagon. Loading is shown for one, two and three containers. In the case for loading with two, different placements are shown - two in the middle or one at each end. The air resistance is shown in Figure 4.9, which shows the effect of the number and placement of the containers.

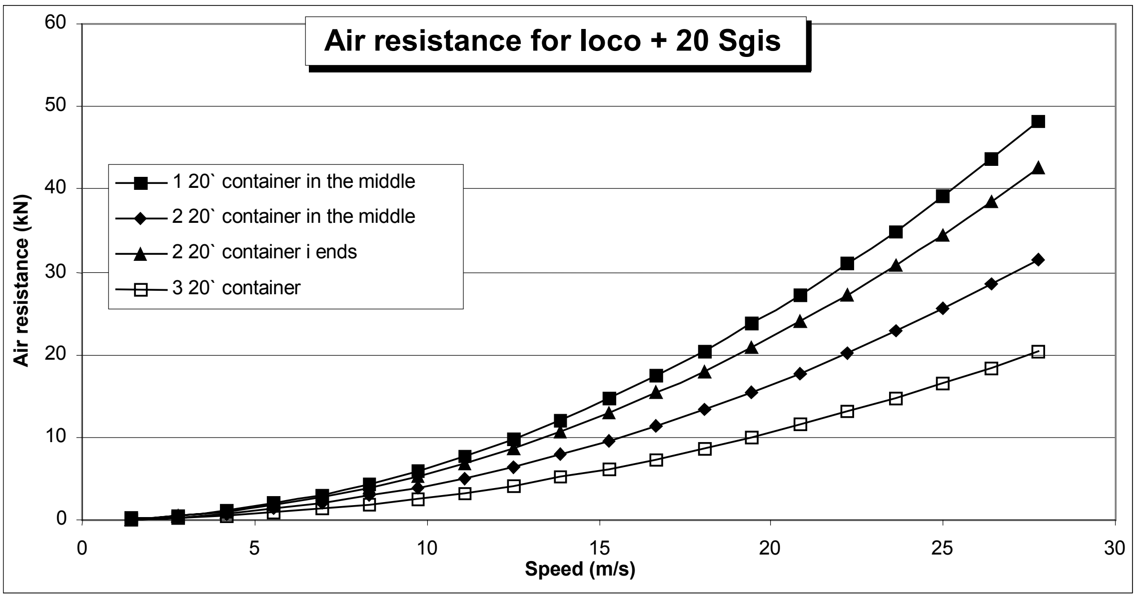


Figure 4.9 Air resistance as a function of speed and container placement for a goods train with four-axle flat cars.

The least resistance occurs in the case where the loading surface of the wagon is fully utilized. This is primarily because there is no space between the containers. Thus there will not be a turbulent airflow between them and the air resistance is not increased. When a single container is placed on the middle of the wagon, there will be a larger space between each container, shown in Figure 4.10. This will cause a large increase in the air resistance, since there will be a turbulent flow between the wagons and their load.

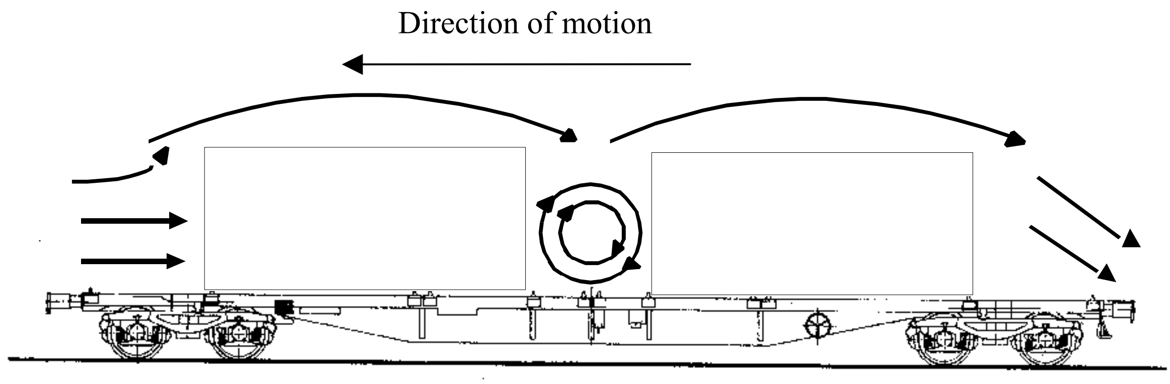


Figure 4.10 Schematic view of air flow around containers on a flat car.

Figure 4.9 shows that there is clearly a greater air resistance when the containers are spread instead of being placed together in the middle. By concentrating the load in the middle, the air resistance can be reduced by about 25%.
In the case where the wagon is loaded with two containers, the load can either be concentrated in the middle of the car or the containers can be placed in each end.

5. Air resistance as a function of train length - homogeneous trains

As an extension of the previous chapter, where air resistance was shown as a function of speed, the dependence of $c_L \cdot A$ on train length will now be shown. Note since a standard reference area of 10 m^2 was chosen, the air resistance coefficient is simply one tenth of the values on the y-axis of the $c_L \cdot A$ plots. In chapter 4, the train size was held constant and the speed variable. When looking at train length, the speed is not important, since the speed dependence is prescribed through Equation 3.1. An overview of the different type of train arrangements is shown in Section 5.4.

5.1 Open Wagons

Figure 5.1 shows the air resistance for the four axle bulk goods wagon type Fad and the open wagon Es (two-axles) and Eaos (four axles). Each wagon is considered in fully loaded and empty condition respectively

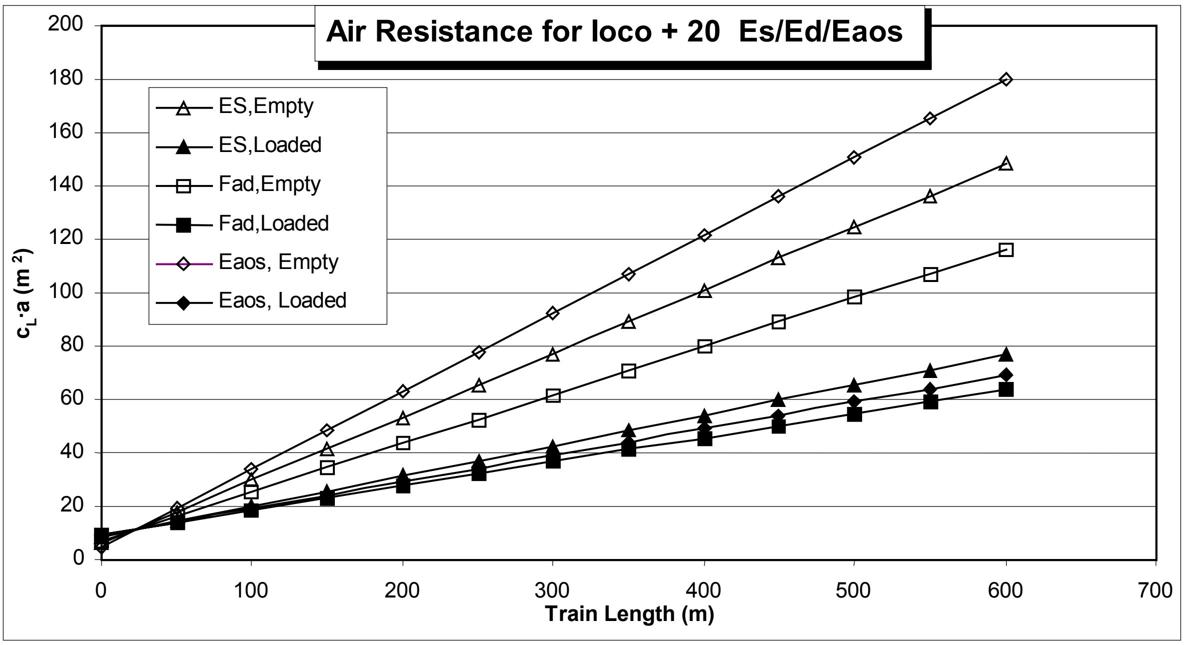


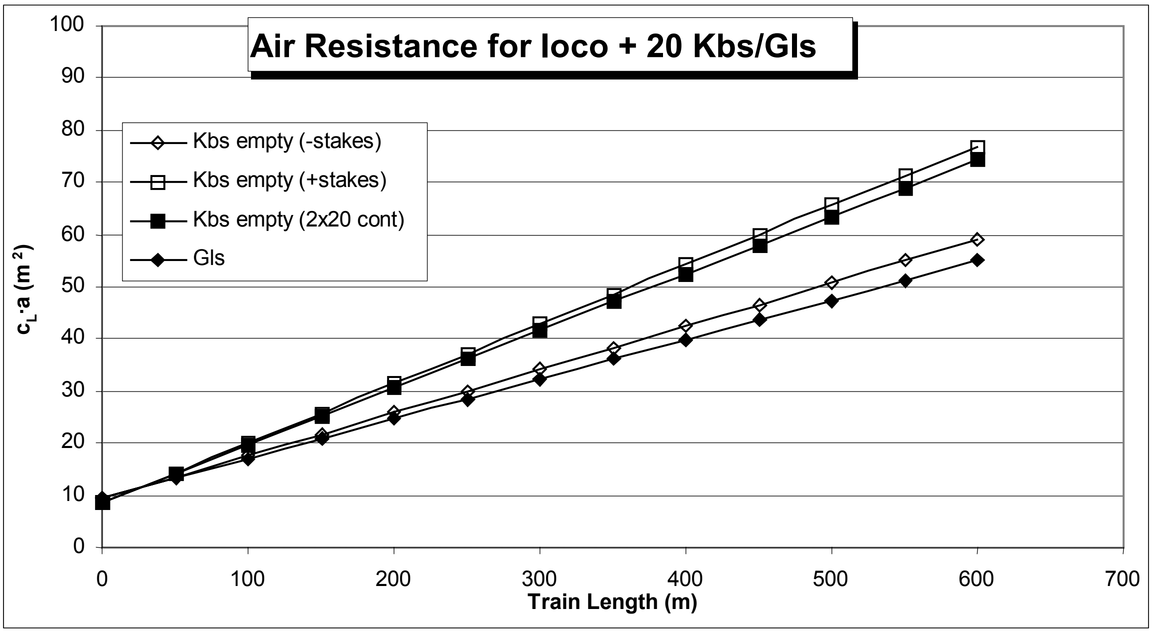
Figure 5.1 Air resistance as a function of train length for wagon suitable for bulk goods transport

The wagons vary most in the empty condition. The large resistance is due to the empty load room, due to aerodynamic effects similar to those shown in Figure 4.10. The largest resistance is found for the four-axle type Eaos. Type Es has a 17 % lower resistance and the type Fad has a 35% lower resistance.

For the loaded wagons, the difference are not so large, here it is the short Es that has the largest resistance, with the long Eaos showing 10% less air resistance and type Fad again having the lowest resistance, 16% lower than the Es. That the order is not the same is due to the different construction, among the details of importance being the size of the load compartment. The best performance is that of the Fad in both cases, because of a more effective aerodynamic design (see Appendix 1).
When comparing the loaded wagons, it is found that the air resistance for the Fad is 45 % lower than in the empty condition. For the ES, the difference is 48% and for the Eaos as large as 62%. The conclusion remains that there are significant aerodynamic advantages to be achieved by covering empty wagons of this type, possibly by some kind of tarpaulin, or plate.

5.2 Open and Closed wagons

For the kbs, it is shown empty with and without the wagon stakes, as well as in a loaded



Figur 5.2 Air resistance as a function of length for open Kbs wagons and closed Gls wagons

condition with 2 20-foot containers in Figure 5.2.

As shown in the previous chapter, there is not much difference between the wagon with and without the stakes or in when loaded with containers (about. 3%). On the other hand, there is a marked difference whether the wagon has stakes, with the difference being 23%. It would therefore be advantageous to take down the wagon stakes when not needed. The closed, two-axle goods wagon Gls, is shown in the same graph, and has a 36 % lower resistance than the kbs loaded with containers.

5.3 Four-axle container wagons

The final case is that of the four-axle container wagon type Sgis, shown in Figure 5.3.

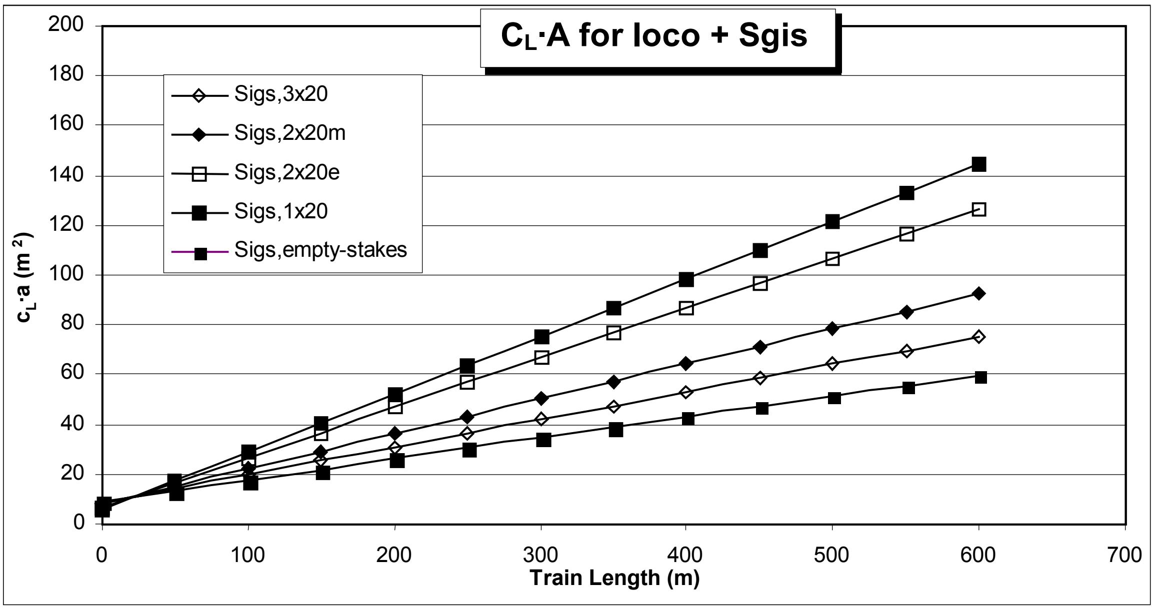


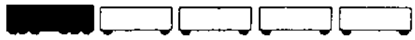
Figure 5.3 Aerodynamic resistance as a function of train length for trains with a four-axle container wagon.

In keeping with the previous chapter, it is the wagon with only one container that gives the greatest air resistance. The next highest is the wagon with 2 containers at the ends of the wagon, which has an air resistance 12 % lower. If the two-container load is placed in the middle of the wagon, the air resistance is about 27% lower than the placement in the end, amounting to 36% lower than the one container wagon. For the case of three containers per wagon, the difference is about 48%, that is to say, half the air resistance of the wagon with only one container. From an aerodynamic point of view, it is advantageous to load the wagon properly, preferably fully loaded with 3 containers or with 2 in the middle. Later, it will be shown that there can be an advantage to carrying empty containers. The air resistance of an empty wagon is 59%

lower than the reference condition of one container per wagon.

5.4 Homogeneous trains

Table 3.1 Equations for calculating the air resistance of different homogeneous trains as a function of train length, Lt, in meters.

Wagon type and arrangement	$C_L \bullet A_{norm}$ - m^2	Description
Kbs no stakes	$9,26 + L_t \bullet 8,31 \bullet 10^{-2}$	
Kbs with stakes	$8,59 + L_t \bullet 11,47 \bullet 10^{-2}$	
Gls	$9,40 + L_t \bullet 7,61 \bullet 10^{-2}$	
Sgis, empty no stakes	$9,24 + L_t \bullet 8,40 \bullet 10^{-2}$	
Sgis, 3x20 ft containers	$8,67 + L_t \bullet 11,10 \bullet 10^{-2}$	
Sgis, 2x20 middle	$8,05 + L_t \bullet 14,05 \bullet 10^{-2}$	
Sgis, 2x20 ends	$6,81 + L_t \bullet 19,96 \bullet 10^{-2}$	
Sgis, 1x20 middle	$6,17 + L_t \bullet 23,01 \bullet 10^{-2}$	
Fad loaded	$9,07 + L_t \bullet 9,17 \bullet 10^{-2}$	
Fad empty	$7,19 + L_t \bullet 18,18 \bullet 10^{-2}$	
Eaos, loaded	$8,89 + L_t \bullet 10,04 \bullet 10^{-2}$	
Eaos, empty	$4,88 + L_t \bullet 29,13 \bullet 10^{-2}$	
Es, loaded	$8,62 + L_t \bullet 11,33 \bullet 10^{-2}$	
Es, empty	$6,02 + L_t \bullet 23,71 \bullet 10^{-2}$	

6. Air Resistance for non-homogeneous trains

In the previous chapter, trains were considered that consisted of the same shape of wagon. It is now of interest to investigate how a freight train is arranged. The question is what is the significance of open and closed cars located next to each other, for example. Or what is the significance of where containers are located on a wagon, or what is the difference of resistance between homogeneous and non-homogeneous trains.

The locomotive and wagons are the same as in the previous chapter. A summary of non-homogeneous trains is found in section 6.3.

As mentioned, the calculations for non-homogeneous trains are more complicated than for homogeneous. The calculations that form the basis of this chapter are shown in Appendix 3.

6.1 Two-axle wagons

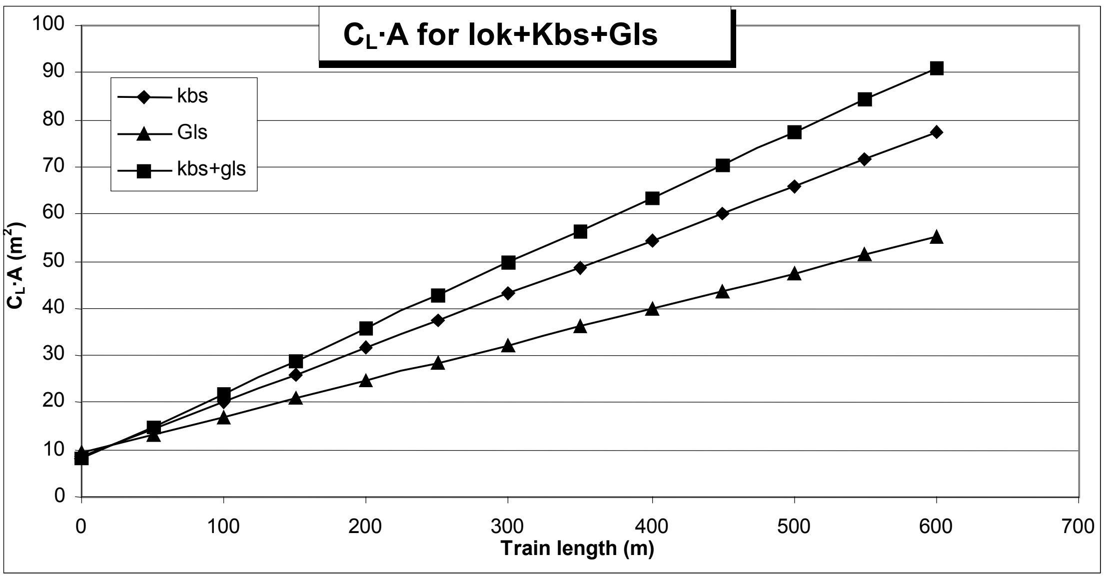


Figure 6.1 Air resistance for trains with different arrangements

The difference between open and closed cars is investigated first. Figure 6.1 shows the air resistance coefficient as a function of train length for three types of trains. Figure 6.1 shows that the air resistance is lowest for the homogeneous train. On the other hand, the highest resistance is obtained with the mixed train. This is because the

train with the mixed wagon types the area exposed to the air motion is much larger than for the homogeneous train as mentioned in Section 3. For the homogeneous trains, the train with the closed wagons gives the lowest resistance relative to the corresponding train with open wagons.
The difference in the air resistance between mixed and homogenous trains is about 40% according to Figure 6.1, if the homogeneous train consists of closed goods wagons and about 15% for flat cars.

6.2 Flat cars

As an extension of the analysis of four-axle container wagons (Sgis) the effect of differing placement of the load in container trains will now be examined.

As shown in the previous chapter, a four-axle container wagon of the type shown here, can be loaded in several ways. They can be empty, with and without stakes, or they can be loaded with one, two or three 20-foot containers. The air resistance is calculated as shown in Chapter 3, and the areas mentioned in Appendix 2 are used.

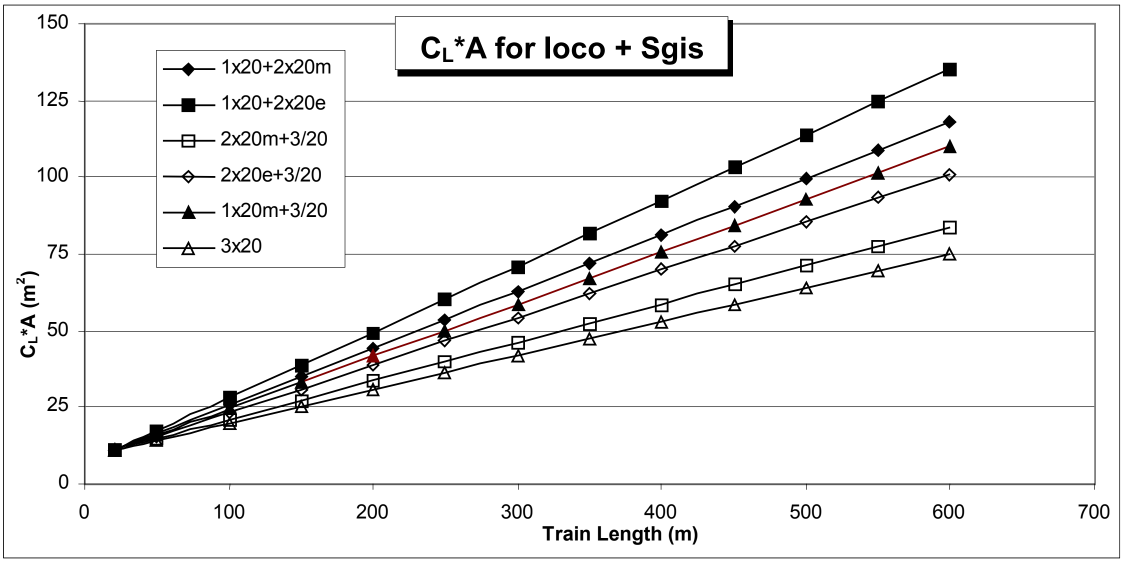


Figure 6.2 Air resistance parameters for a train consisting of flat cars with different configurations of container loading.

Figure 6.2 shows c_L*A for four different arrangements of the load. To reduce complexity, there are only two different wagons in each train. For comparison purposes, the air resistance for a homogeneous train with three containers on each wagon (the optimum arrangement) is included. The figure shows that the greatest air resistance is found for the least loaded wagon. As mentioned in Chapter 4, the air resistance is lowered by placing the containers in the middle of the wagon instead of at the ends. The same is seen in figure 6.2. In addition, it is shown that for fewer containers per wagon, the worse the aerodynamic characteristics of the wagon. By using three containers per wagon instead of one, a reduction in air resistance of about 30% is attained.

Then from the aerodynamic point of view, it is most advantageous to fully load the wagon. The effect of this on rolling resistance is shown in a subsequent chapter. As mentioned, there is a difference depending on whether the containers are placed in the middle of the wagons or at the ends. But since this difference is included in the $C_{L,M}$-values, no extra area shall be calculated with the associated $C_{L,F}$-value from the use of Equation 3.3.

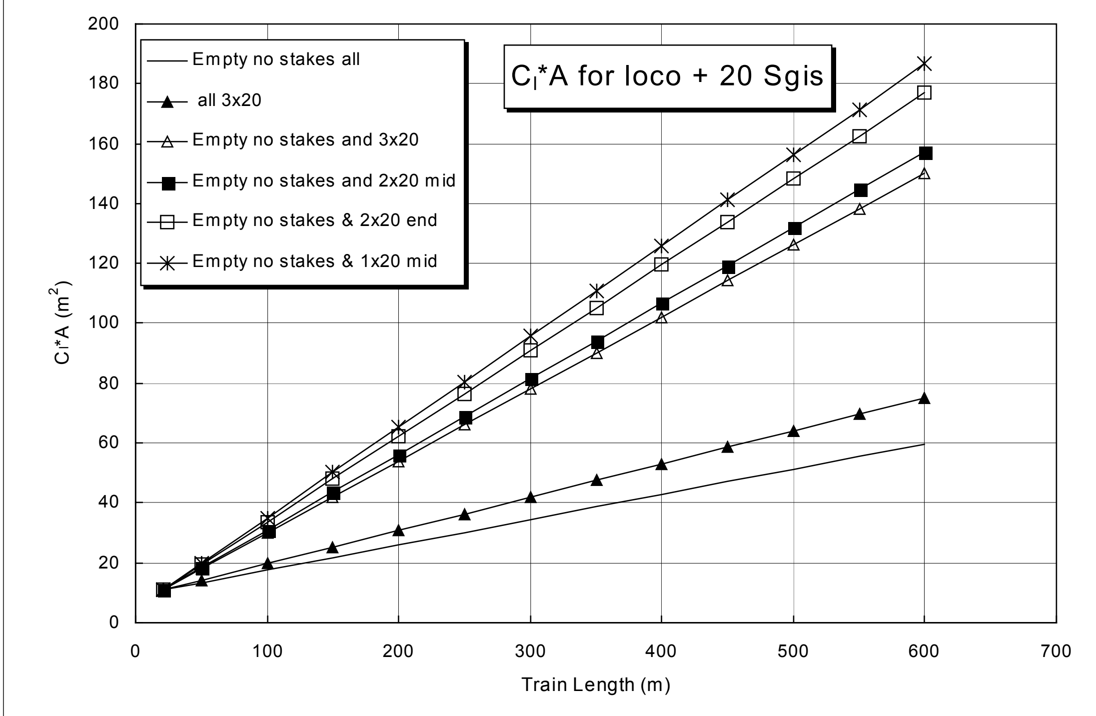


Figure 6.3 Air resistance of non-homogeneous trains with empty flat cars mixed with different configurations of container loading

Figure 6.3 shows the remaining combinations of loaded and unloaded wagons, again compared to the homogeneous train:

The figure does not show the same spread between the inhomogeneous trains shown in Figure 6.2. There is, though, a large difference between the homogeneous and inhomogeneous trains. The two homogeneous trains have only about half of the air resistance of the mixed trains. Again, it is advantageous to load the wagons uniformly.

The difference between the inhomogeneous trains:
The largest air resistance is obtained with trains than have an alternative wagon with one container and an empty wagon. The large resistance is caused by the freely standing container. By concentrating the containers on fewer wagons and decoupling the empty wagons, the air resistance could be reduced by up to about 50%. By placing an extra container on the loaded wagon, the value of F_L is reduced bay about 3% if they are placed at the ends of the wagon. By setting the container on the middle of the wagon or using three containers per wagon instead of one, F_L can be reduced by about 10%.

6.3 Non-homogeneous trains.

The results from the trains can be written as linear functions of the train length. These equations are given in table 6.1

Table 6.1 Equations for calculating the aerodynamic resistance of the non-homogeneous trains discussed in Chapter 6.

Wagon type and arrangement	Air resistance, $C_L \bullet A_{norm}$	Description
Sgis, 2x20 middle/3x20	$8,35 + L_t \bullet 12,58 \bullet 10^{-2}$	
Sgis, 2x20 end/3x30	$7,74 + L_t \bullet 15,53 \bullet 10^{-2}$	
Sgis, empty no stakes/1x20 middle	$4,63 + L_t \bullet 30,33 \bullet 10^{-2}$	
Sgis, empty no stakes /3x20	$5,95 + L_t \bullet 21,06 \bullet 10^{-2}$	
Sgis, 2x20 middle/ empty no stakes	$5,69 + L_t \bullet 25,27 \bullet 10^{-2}$	
Sgis, 2x20 endes/ empty no stakes	$4,99 + L_t \bullet 28,64 \bullet 10^{-2}$	
Sgis, 1x20 middle/3x20	$7,42 + L_t \bullet 17,06 \bullet 10^{-2}$	
Sgis, 2x20 ende1x20 middle	$6,49 + L_t \bullet 21,49 \bullet 10^{-2}$	
Sgis, 2x20 middle/1x20 middle	$7,02 + L_t \bullet 18,53 \bullet 10^{-2}$	
Gls/Kbs	$8,17 + L_t \bullet 13,49 \bullet 10^{-2}$	

7 Comparison with other measurements

As mentioned previously, the resistance coefficients were obtained on the basis of the German test values obtained in wind tunnel tests for the respective locomotives and wagons. The measurements were then made more user-friendly by adapting the values for the locomotives such that one does not have to consider the placement of the individual wagon in the train (middle or ends). In order to give an analysis of the utility of the numbers, it is the purpose of this chapter to compare the individual German measurements with Swedish Measurements.

In reference 2, the results of the Swedish measurements are given and analyzed. In contrast to the German values, the Swedish values are based on measurements for complete trains during normal operation. Instead of using a wind tunnel, a measurement wagon was located in the train. There are variations connected with the measurement wagon being in the train, but through a comparison, it is possible to evaluate to what extent the German values and calculation methods agree with ”real trains”:

7.1 Comparison with closed Goods wagons.

As a first example, the air resistance for closed goods wagons is investigated. The difference in air resistance is given in Figure 7.1.
The figure shows that there is good agreement between the German and Swedish values. It should be noted that the measurement wagon that is used in the Swedish measurements is included in their values, but that it has a minimal effect on the results.

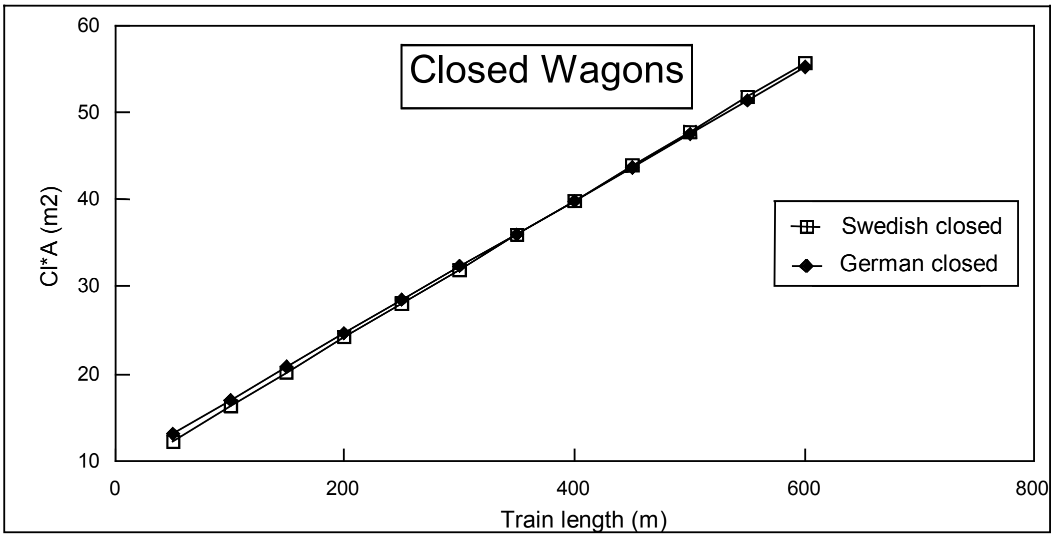


Figure 7.1 Comparison of measured air resistance (Swedish) to calculated air resistance (German) for closed goods wagons.

7.2 Comparison of flatcars

For flatcars, the agreement is not as good. Figure 7.1 shows that for a two-axle kbs, the calculation estimates that there is about 20% less air resistance than for a similar Swedish wagon. The difference should be seen in light of the physical differences between the kbs and the Swedish flatcar. As can be seen in Appendix 1, the Swedish car differs on some significant points. One is the high sides, that make the wagon look more like an open wagon, such as the litra Es.

For comparison purposes, the completely flat Sgis, though with stakes, is considered, since it can be more readily compared to the two other wagons. This gives a lower air resistance, since contrary to the other, it is complete flat when the stakes are disregarded, and then better aerodynamically in many ways. Taking construction differences into consideration, it is concluded that there is a reasonably good agreement between the values for the different wagons and that the values used for the Sgis and Kbs are adequate. The percent differences are that the kbs and sgis give an air resistance that is 21 and 39 % less respectively than for the Oms.

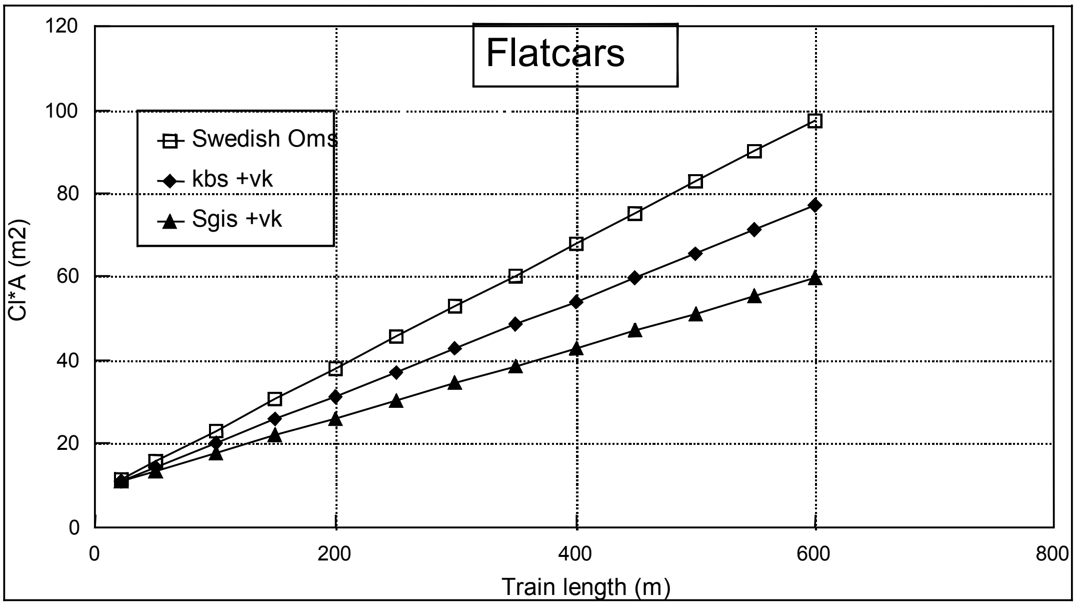


Figure 7.2 Comparison of predicted air resistance to measured air resistance (Swedish) for empty flat cars.

7.3 Comparison of inhomogeneous trains

In the preceding section the calculation for the homogeneous trains was compared with the measured values and found to be acceptable. Therefore, inhomogeneous trains will now be compared.

In Reference 2, the air resistance (c_L*A) for a train with mixed flat Oms and closed Hbikks is presented. The only corresponding train that is treated here in the report is the train with a mixture of flat kbs and closed Gls.

The air resistance is shown in Figure 7.3.

Figure 7.3 shows that there is in essence no difference between the measured data and the estimates from wind tunnel based correlations. The maximum variation is only 3,5% for the longest train. There may be a weak point in the calculation for the kbs/Oms. In the calculation of the difference in the area between the Kbs and the closed Gls (which has the largest frontal area) the stakes of the kbs are included in the frontal area. As Figure 4.6 shows, the wagon's air resistances with stakes or container are close to each other. Therefore, it is reasonable to assume that the stakes have almost the same effect as the containers. Though, this cannot be proven and there for must be considered a weakness in the calculation.

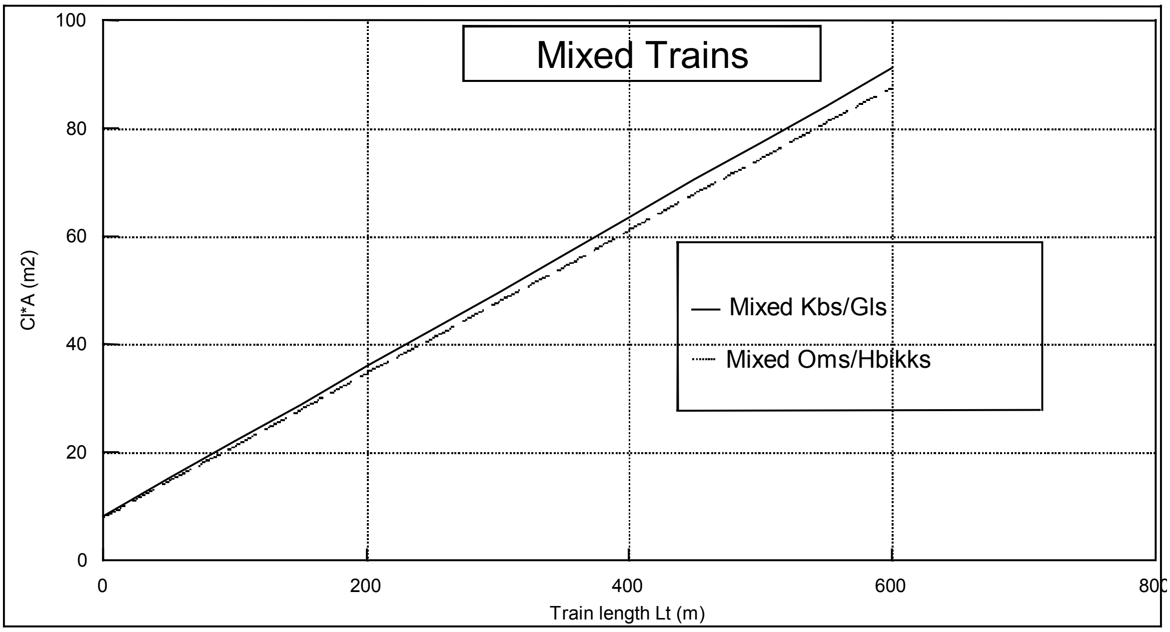


Figure 7.3 Comparison of measured air resistance (Oms/Hbikks) to estimated air resistance for mixed trains.

8. Calculation of rolling resistance

Two factors normally determine the rolling resistance of a vehicle. The first is the weight, which is not a train parameter, but an operational variable. The second is the rolling resistance coefficient, f_r. This is a parameter for the type of train/wagon involved in the calculation.

8.1 Calculation method

For vehicles with stiff wheels, where the wheels do not deform plastically, the general relation for rolling resistance with flat terrain is used:

$$F_R = f_R \cdot m_{tog} \cdot g \qquad (8.1)$$

Where: F_R is the train's total rolling resistance in N
f_R is the rolling resistance coefficient (dimensionless)
m_{tog} is the weight of the train in kg
g is the acceleration of gravity in m/s^2

It should be noted that Equation 8.1 expresses the maximum rolling resistance. That is to say, the equation does not apply if there is slip between the wheel and the rails. For wagons, slip is very rare, since the wheels are not driven. On the other hand, slip can more likely occur with the locomotive, especially under starting condition. Slip is not further considered, during acceleration, nor under braking, which is a separate topic.

The weight of the train is normally given, and g is a constant. On the other hand, f_R can be more difficult to establish, since the coefficient can depend on mass, number of axles, axle load and several other variables. In practice, f_R is determined through measurements for the wheel in question under different operating conditions.

The following is a description of a method for an approximate calculation of the rolling resistance of different train shapes. It is assumed that the rolling resistance coefficient is dependent on the speed of the train. The general formula for the calculation of f_R is given as (1):

$$f_R = C_0 + C_1 \cdot \left(\frac{\nu}{\nu_0}\right) + C_2 \cdot \left(\frac{\nu}{\nu_0}\right)^2 \qquad (8.2)$$

Where:

f_R is the rolling resistance coefficient in ‰.

C_0, C_1 and C_2 are constants in ‰ .

ν is the speed of the train in m/s

ν_0 is a constant, 100 km/h = 27,778 m/s

The constant C_0 can be calculated as [7]:

$$C_0 = \frac{f_{SL} + m_L + f_{SV} + m_V}{m_{tog}} \qquad (8.3)$$

Where:

f_{SL} is the starting value for a locomotive's rolling resistance (dimensionless).

m_L is the locomotive weight in kg.

m_V is the total weight of the wagons in i kg.

m_{Tog} is the total weight of the train in kg.

f_{SV} is an initial value for the rolling resistance of the wagon (dimensionless), and can be calculated as:

$$f_{SV} = C_{CV} + \frac{F_A}{G_A} \qquad (8.4)$$

Where:

C_{SV} is a constant in ‰

F_A is an axle pressure constant of 100 N

G_A is the average axle load for the train in kN.

Since the average axle load is the train's total load divided with the number of axles (n_{ax}) substitution into Equation 10 yields:

$$f_{SV} = C_{CV} + \frac{F_A \cdot n_{ax}}{m_{tog} \cdot g} \qquad (8.5)$$

The constants for the calculation of rolling resistance are given in Reference (1)

Table 8.1 Constants for the calculation of rolling resistance:

Four axle locomotive	f_{SL} = 2,5 - 3,5 ‰	
Six axle locomotive	f_{SL} = 3,5 - 4,5 ‰	
ICE- motor wagon	f_{SL} = 1,3 ‰	
ICE- middle rwagon	f_{SV} = 0,60 ‰	
ICE	C1 = 0,10 ‰	C2 = 0,3 ‰
Passenger train	C_{SV} = 0,40 ‰	
	C1 = 0,25 ‰	C2 = 0,50 ‰
Goods train	C_{SV} = 0,60 ‰	
	C1 = 0,50 ‰	C2 = 0,60 ‰

As an example, consider a goods train consisting of a six-axle locomotive (123 ton) and a string of cars consisting of ten two-axle wagons á 40 tons - a total of 513 tons. The train is considered to operate at 100 km/h = 27,778 m/s.

The train's axle load is calculated as the average value between the locomotive and the wagons.

$$G_A = \frac{400 \cdot 10^3 \cdot 9{,}82\, {}^{m}\!/_{s^2}}{(2 \cdot 10\text{axles})} = 196400\text{N} = 196{,}4\text{kN}$$

The value of f_{SV} is first determined from Equation 10.

For car strings, C_{SV} is found in Table 8.1 to be 0,6 10^{-3}, and for the locomotive, f_{SL} is read to be about. 4 10^{-3}.

$$f_{SV} = 0{,}6 \cdot 10^3 + \frac{100\text{N}}{196400\text{N}} = 0{,}001109 = 1{,}11‰$$

The result for f_{SV} is inserted into Equation 8.4:

$$C_0 = \frac{4 \cdot 10^{-3} \cdot 123 \cdot 10^3\,\text{kg} + 1{,}11 \cdot 10^{-3} \cdot 400 \cdot 10^3\,\text{kg}}{123 \cdot 10^3\,\text{kg} + 400 \cdot 10^3\,\text{kg}} = \frac{936\text{kg}}{523 \cdot 10^3\,\text{kg}} = 1{,}790 \cdot 10^{-3}$$

Using Equation 8.3, f_R:

$$f_R = 1{,}790 \cdot 10^{-3} + 0{,}50 \cdot 10^{-3} \cdot \left(\frac{27{,}778 m/s}{27{,}778 m/s}\right) + 0{,}6 \cdot 10^{6} \cdot \left(\frac{27{,}778 m/s}{27{,}778 m/s}\right)^2 = \underline{2{,}312 \cdot 10^{-3}}$$

8.3 Rolling resistance coefficient f_R

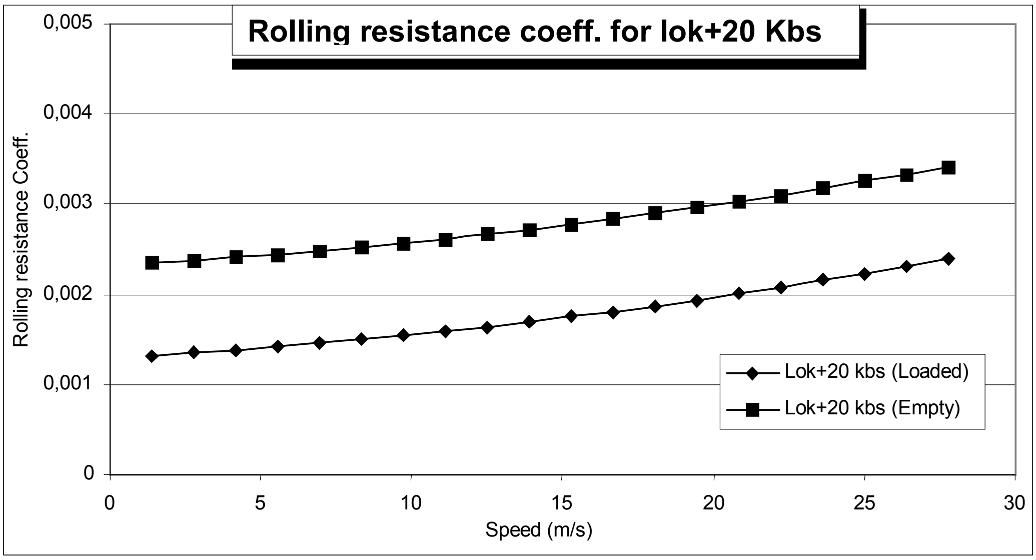


Figure 8.1 Calculated rolling resistance coefficient for a goods train loaded and empty

The results from the previous example have been applied to a goods train with a locomotive and 20 kbs wagons, loaded and empty. The results are shown in Figure 8.1. There are two things to note in Figure 8.1.

For the first, f_R is not independent of speed. For the empty train shown, f_R varies with a factor of two. For trains with a large speed variation, consideration of the variation of f_R with speed is desirable. Secondly, f_R is larger for the empty train than for the full train. This is because G_A in Equation 8.3 is larger for the loaded train. Then F_A/G_A is lowest for the loaded train, and C_0 is 12,95 10^{-4} for the loaded train as opposed to 23,19 10^{-4} for the empty.

9 Rolling resistance for goods trains

In the previous chapter, a method was presented for calculating the rolling resistance for a given train of known composition. This method is fairly comprehensive and it is advantageous to be able to calculate F_R more simply.

9.1 General

As was shown in the previous chapter F_R depends on factors such as axle load, as well as several constants. The axle load and the weight have the result that a number of wagons will be similar when considering F_R. For example, the two-axle wagon will have about the same axle load with the loading is about the same. This is in contrast to the aerodynamic loading, F_L, which is very dependent on the shape of the wagon and its placement in the wagon string. This means that it is possible to approximate F_R, while a calculation of F_L will require more details for the individual wagons.

To a good approximation, the rolling resistance F_R can be written as a linear function of the speed:

$$F_R = A + B \cdot v \qquad (9.1)$$

where:

A is a constant in [N], that depends on the number of axles, that is, the number of wagons. The locomotive is not considered here.

B is a constant in [N s/m] dependent on the train length. The locomotive is considered here.

v is the train speed in [m/s].

Generally, (there can be exceptions) deviations from this method compared to that in the previous chapter be on the order of 2-4 %. Given other variations in modeling, this is quite acceptable. The individual variation for the individual train strings will be shown in the following.

In section 9.4 an approximate expression for the rolling resistance for different goods trains is shown. Also shown are descriptions, compositions, as well as the axle load and the speed dependent expression for rolling resistance. Specific data for the different locomotives and wagons are shown in Appendix 1.

9.2 Bulk goods wagons

The rolling resistance for a train with a different wagon type is shown below. Here, the train (Figures 9.1 and 9.2) consists of Fad-wagons instead of Sgis-wagons. The

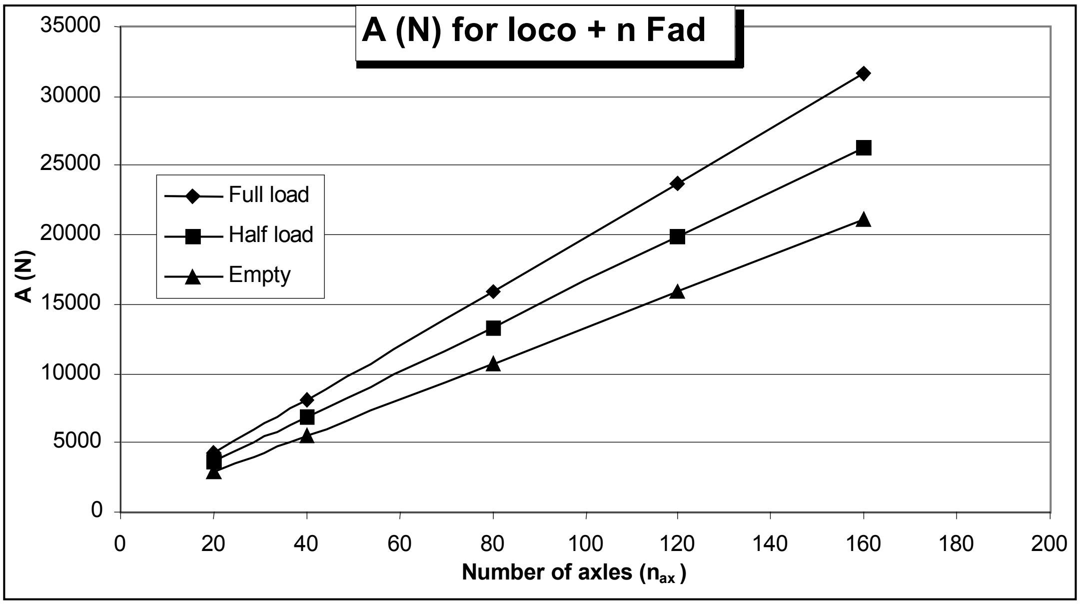


Figure 9.1 Constant, A, from Eq. 9.1 for rolling resistance calculation for bulk goods wagon

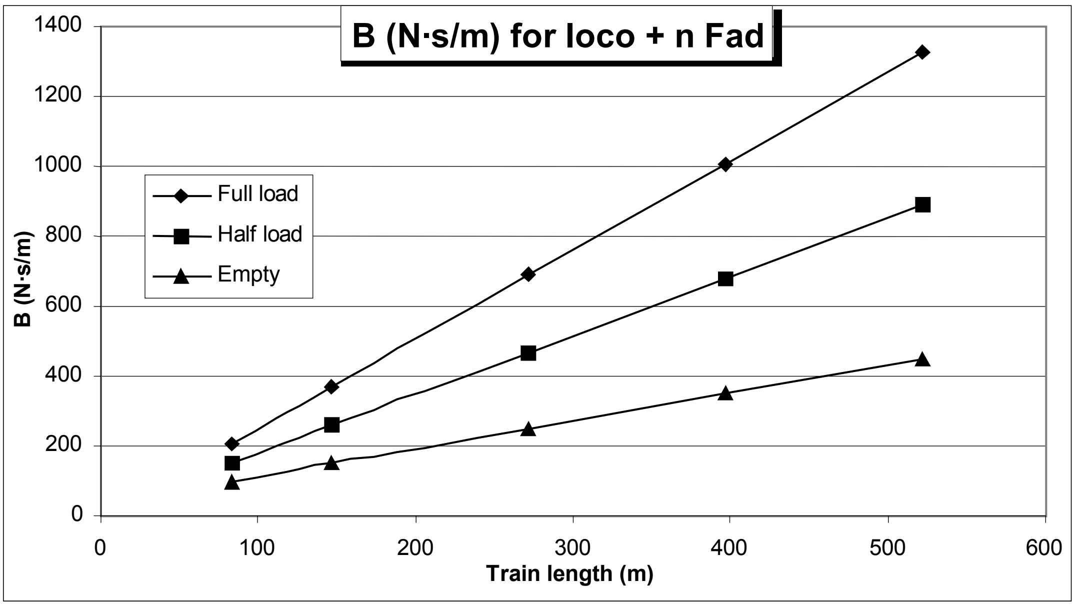


Figure 9.1 Constant, B, from Eq. 9.1 for rolling resistance calculation for bulk goods wagon

rolling resistance constants A and B are shown for full load, half load, and empty.

The total rolling resistance can be calculated from these figures. For a given train composition, A and B can be read from the figure and used in Equation 9.1, after which a speed dependent value of the rolling resistance in possible. It should be noted that the locomotive is included in the determination of B.

When A and B are compared for Sgis and Fad, it is directly apparent from Figure 9.1 and 9.3 that the A-values are basically the same. This is because the A-value is depicted as a function of the number of wagon axles, and since both wagon have four axles, the A-values should be nearly the same. The B-values are different. The reason is that B is a function of the train length and that litra Fals is 12,24 m long as opposed to litra Sgis's length of 19,64 m, so the former will have a larger B-value

<u>9.3 Flat cars.</u>

The first goods wagon type is the four-axle wagon, here being the Sgis-wagons that are analyzed. The values of A and B for determining the rolling resistance are shown for four cases: Fully loaded: three containers per wagon. 2/3 loaded, that is 2 containers per wagon as well as 1/3 loaded, that is one container per wagon. Finally, an empty train is shown. The results are shown in Figures 9.3 and 9.4

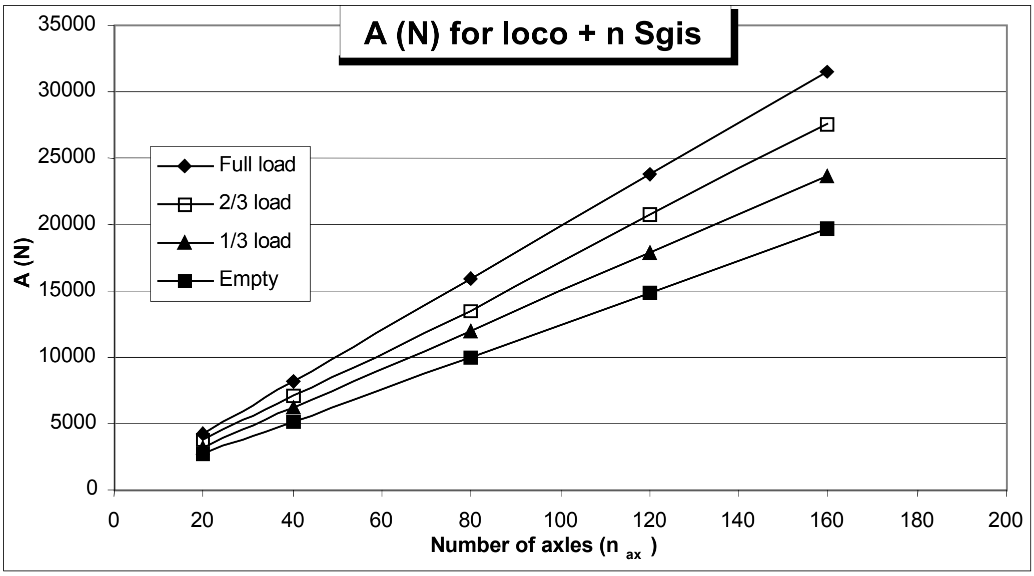


Figure 9.3 Constant, A, from Eq. 9.1 for rolling resistance calculation for 4-axle flatcars

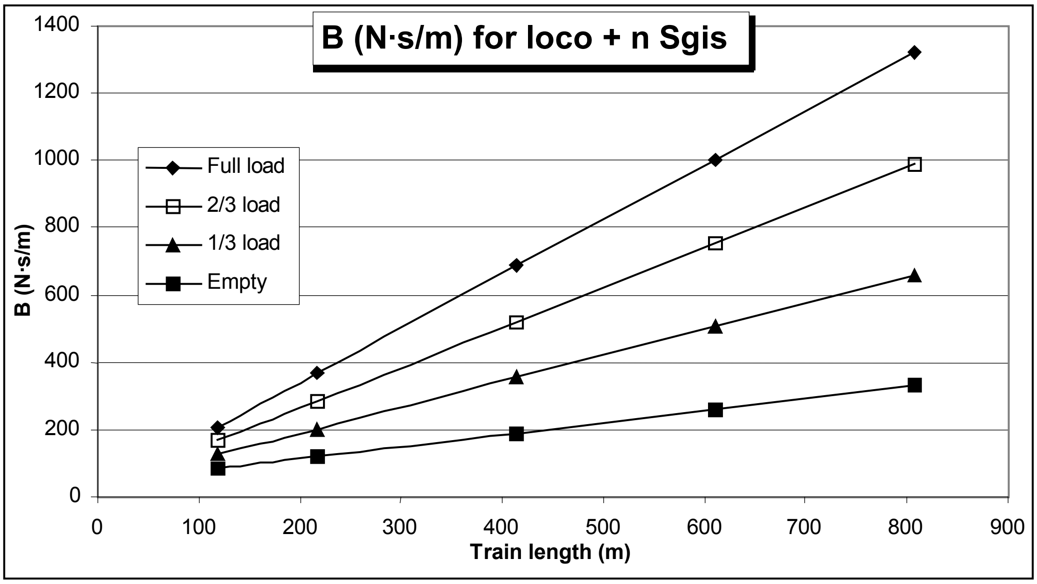


Figure 9.4 Constant, B, from Eq. 9.1 for rolling resistance calculation for 4-axle flatcars

Figures 9.5 and 9.6how A and B values for a goods train consisting of two-axle wagons. The three trains shown are fully loaded, without load, and with one container per wagon, that is, half load.

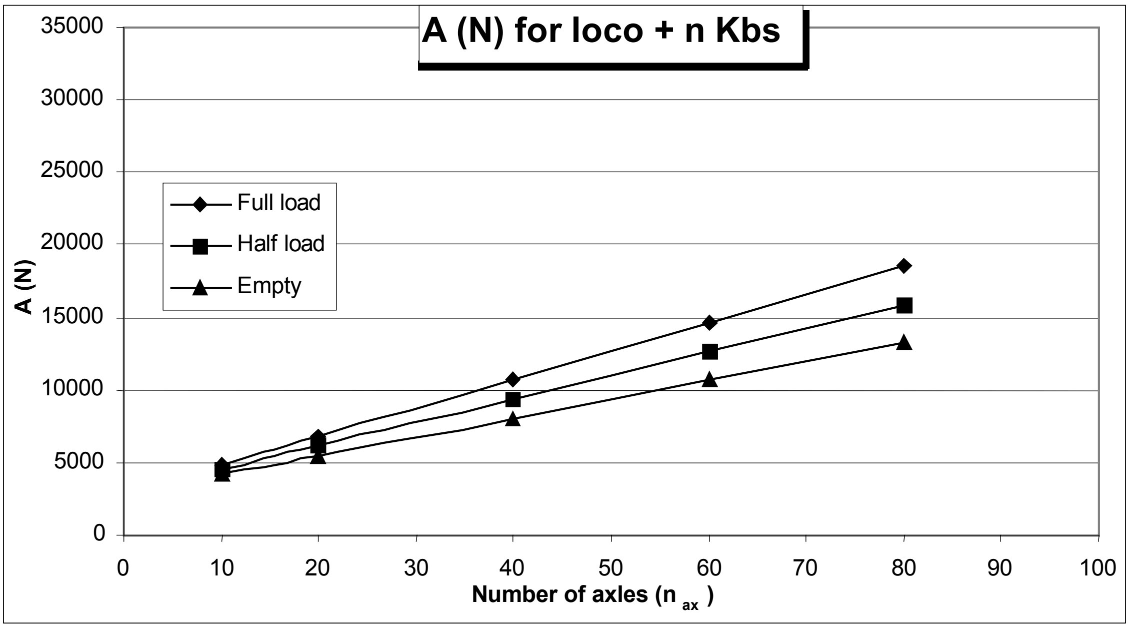


Figure 9.5 Constant, A, from Eq. 9.1 for rolling resistance calculation for 2-axle flatcars

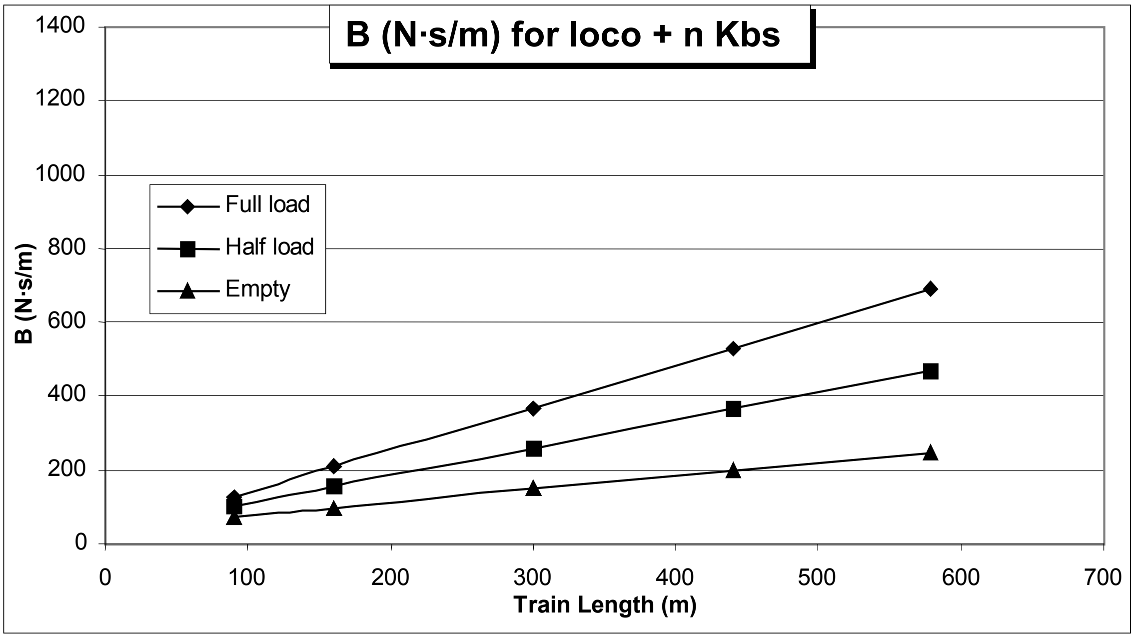
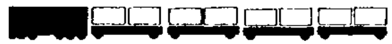


Figure 9.6 Constant, B, from Eq. 9.1 for rolling resistance calculation for 2-axle flatcars

A and B are half as large as for the two-axle wagons as for the rour-axle wagons, corresponding to the difference in the number of axles per wagon.

Table 9.1 Configuration of homogeneous trains

Train type	Length - m	Mean axle load - kN	A - N	B - N-s/m	Description
loco + n Sgis 3 containers/wagon	21+n·19,64	195,4	$343+195 \cdot n_{ax}$	$15{,}14+1{,}62 \cdot L_t$	
loco + n Sgis2 containers/wagon	21+n·19,64	144,7	$231+170 \cdot n_{ax}$	$23{,}96+1{,}20 \cdot L_t$	
loco + n Sgis 1 containers/wagon	21+n·19,64	93,94	$344+146 \cdot n_{ax}$	$32{,}89+0{,}78 \cdot L_t$	
loco + n Sgis unloaded	21+n·19,64	43,21	$344+121 \cdot n_{ax}$	$344+121 \cdot n_{ax}$	
loco + n kbs 2 containers/wagon	21+n·13,96	196,4	$2881+195 \cdot n_{ax}$	$25{,}10+1{,}14 \cdot L_t$	
loco + n kbs 1 container/wagon	21+n·13,96	128,9	$2881+165 \cdot n_{ax}$	$33{,}36+0{,}75 \cdot L_t$	
loco + n kbs unloaded	21+n·13,96	61,4	$2881+130 \cdot n_{ax}$	$41{,}62+0{,}36 \cdot L_t$	
loco + n Fals fully loaded	21+n·12,54	196,4	$344+195 \cdot n_{ax}$	$-4{,}38+2{,}55 \cdot L_t$	
loco + n Fals half loaded	21+n·12,54	128,9	$344+162 \cdot n_{ax}$	$14{,}01+1{,}67 \cdot L_t$	
loco + n Fals unloaded	21+n·12,54	61,4	$344+130 \cdot n_{ax}$	$32{,}71+0{,}82 \cdot L_t$	

10 Total rolling resistance

Using the coefficients A and B it is now possible to calculate the total rolling resistance. This is shown below for the trains of the previous section. Since F_R is proportional to the train weight the total rolling resistance is dependent on the loading of the trains.

Figure 10.1 shows the rolling resistance for the litra Sgis.

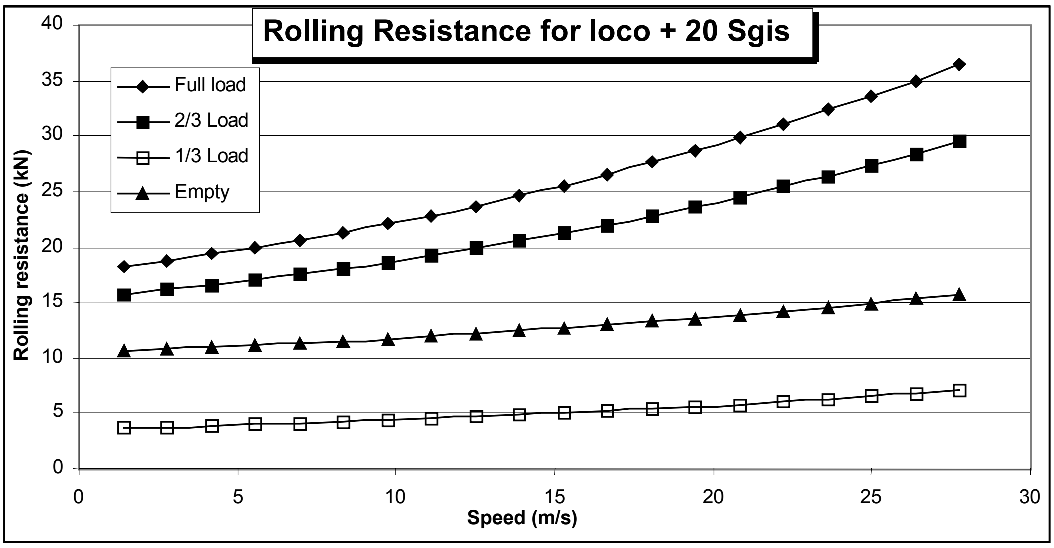


Figure 10.1 Rolling resistance for a goods train with Sgis wagons for varying loads.

The figure shows that the fully loaded train has the greatest rolling resistance, and the other trains follow according to loading. With 2 containers per wagon F_R is about 17 % less. For one container per wagon, F_R is about 34 % less, and with empty wagons, F_R is about 51 % lower than with full load. In other words, every time the load drops by 1/3 F_R becomes about 17 % less.

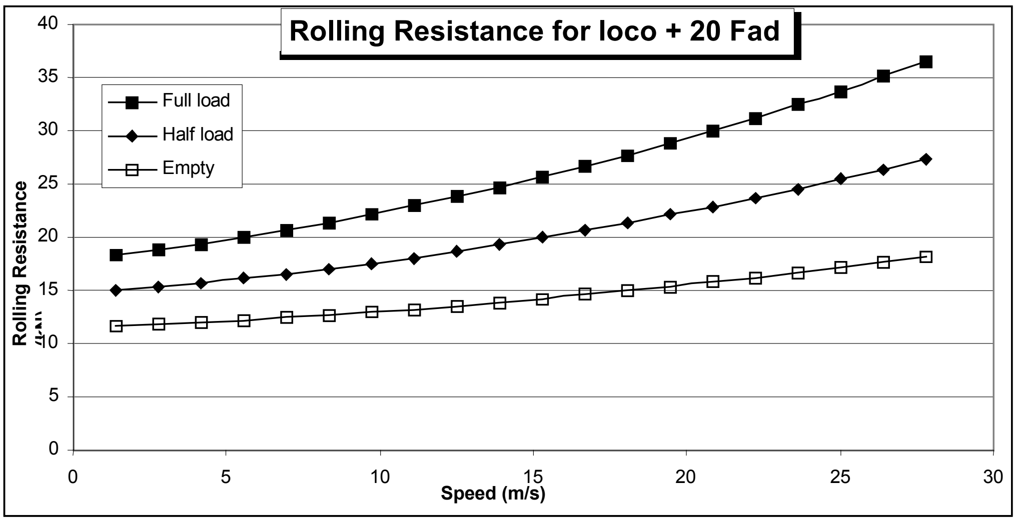


Figure 10.2 Rolling resistance for a goods train with Fadwagons for varying loads.

Figure 10.2 shows the rolling resistance for a locomotive and lok+20 Fad wagons. It is seen that the rolling resistance follows that same pattern as for the Sgis. Here, the half loaded train give a value of F_R that is about 23 % lower than the fully loaded train. The empty train has a rolling resistance that is about 46% lower.

While there was a clear pattern within each type of wagon, a comparison of the two wagon types (Sgis og Fad) does not give as clear a picture. The difference between full load and empty is 51 and 46% respectively. The difference is primarily because the relationship between the tare weight and the maximum load is different for the two wagon types, see Appendix 1:

$$\mu_{L,Sgis} = \frac{62}{17{,}6+62} = 77{,}9\%$$

$$\mu_{L,Fad} = \frac{55}{25+55} = 68{,}8\%$$

If the maximum load factor for the two types of wagons was the same, there would be no relevant difference in F_R. Therefore, in principle, for good accuracy, one should include more wagon types than are mentioned here in this section. For the sake of clarity, though, this is not done here. Since the rolling resistance does not depend on the form of the wagon or its placement in the car string, it is possible to use an approximate expression for the other 8 wagon types presented. This approximation will depend on the specifics of the wagons as well as their similarity to the two types discussed.

The next type is the two axle kbs.

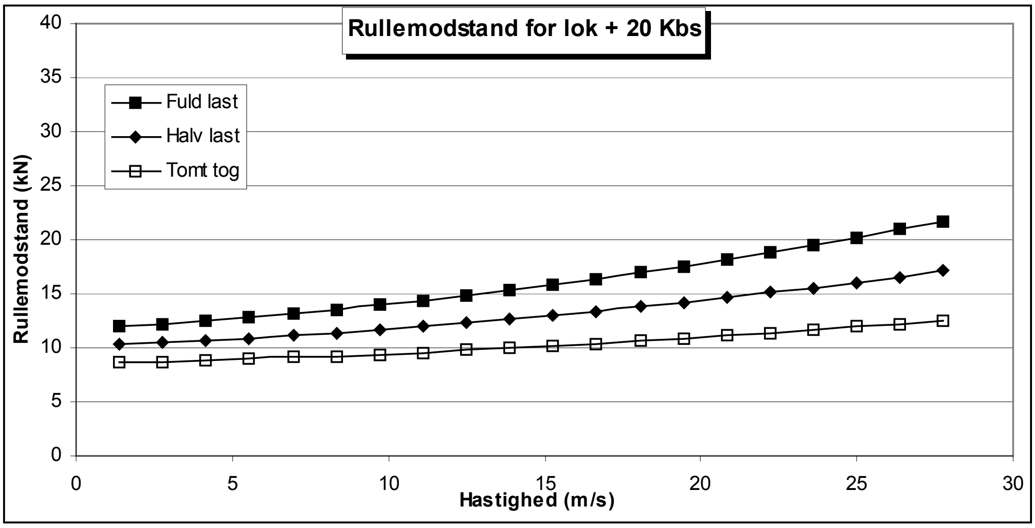


Figure 10.2 Rolling resistance for a goods train with Fadwagons for varying loads.

With half load, F_R is about 19 % less than full load, and for empty wagons, F_R is about 38 % less than for full load. The difference is 19%, even though the maximum load factor is the same as for litra Fad:

$$\mu_{L,Kbs} = \frac{27{,}5}{27{,}5 + 12{,}5} = 68{,}8\%$$

11. Comparison of rolling resistance

After the description and analysis of the calculation method for rolling resistance, is it appropriate to compare with data from the Swedish measurements Reference 2. As mentioned in Section 9, the rolling resistance can be approximated as a function of speed by the equation:

$$F = A + B \cdot v \qquad (9.1)$$

Where:

A is a constant in [N], that depends on the number of wagon axles, locomotive not included.

B is a constant in [N s/m] that depends on the entire length, including the locomotive.

υ is the train speed in [m/s].

11.1 Comparison between flat cars

The comparison here is made between a train consisting of German kbs wagons and the very similar Swedish Oms wagons. A and B are compared individually. Figure 11.1 shows the constant A as a function of the number of axles.

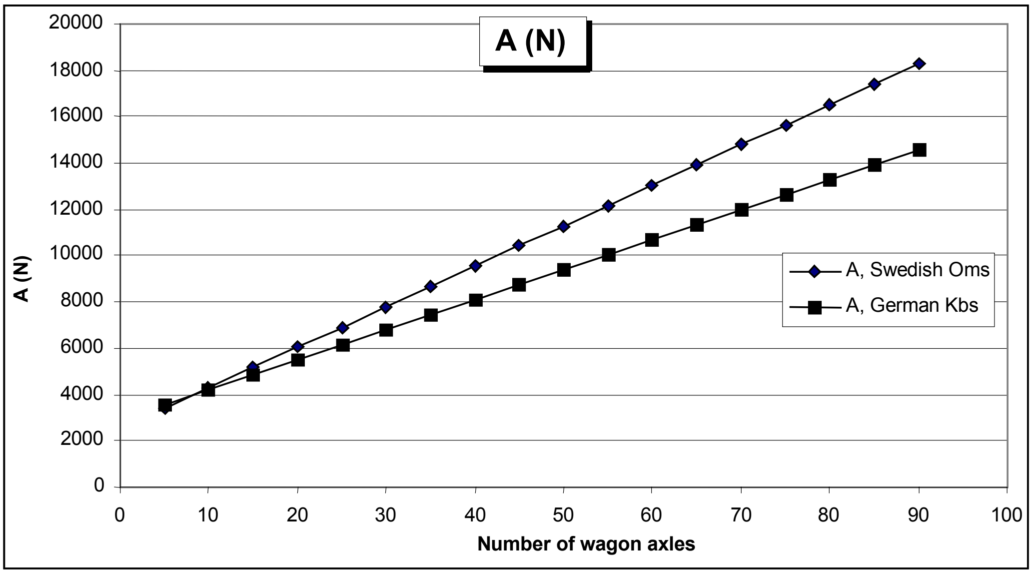


Figure 11.1 Comparison of measured (Swedish) rolling resistance parameter A and the estimated value.

For smaller trains, (up to about 15 axles) there is little difference. The difference increases with the number of wagons, and with a larger goods train with 40 axles and above, the difference is about 20 %.

For the constant B, shown in Fig. 11.1, the pattern is different.

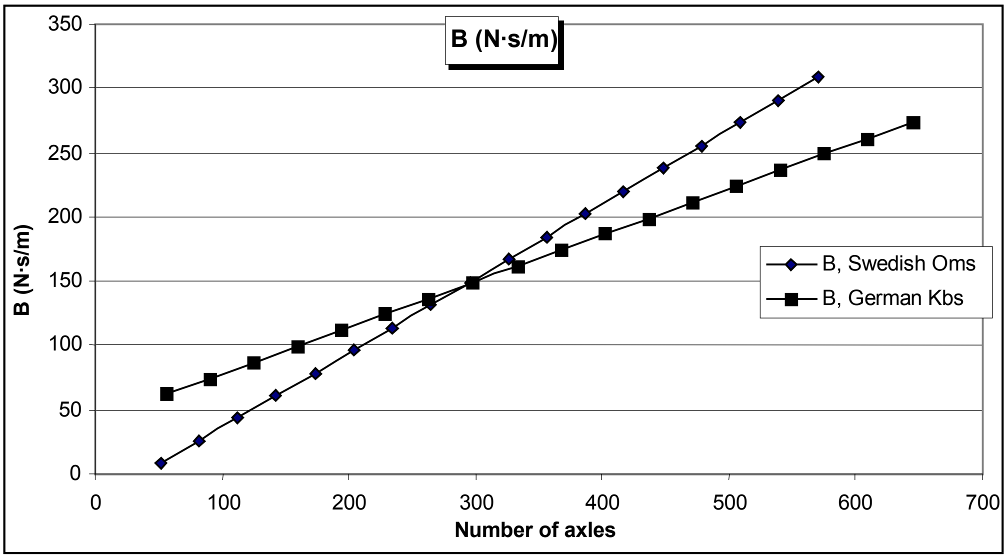


Figure 11.2 Comparison of measured (Swedish) rolling resistance parameter B and the estimated value.

The intersection for the two lines is at a train length of about 350m. For trains less than 150 m long and over 450 m the difference is noticeable. The difference between the two B values is from 30 N s/m up to 50-60 N s/m. For train lengths over 450 m the difference will be between 30 to 50%. Between about 200m and 400m the two values agree fairly well.

11.2 Comparison between mixed goods trains

Since the rolling resistance is determined by both A and B, the question now is, how does the total rolling resistance vary for the two trains. The rolling resistance for a train consisting of the same number of German Kbs and Swedish Oms is shown in Fig. 11.3. Since the final rolling resistance is dependent on the total number of axles and the speed, the rolling resistance is shown for trains with 10, 20 and 40 wagons. This is because A and B vary in different amounts depending on the size of the train.

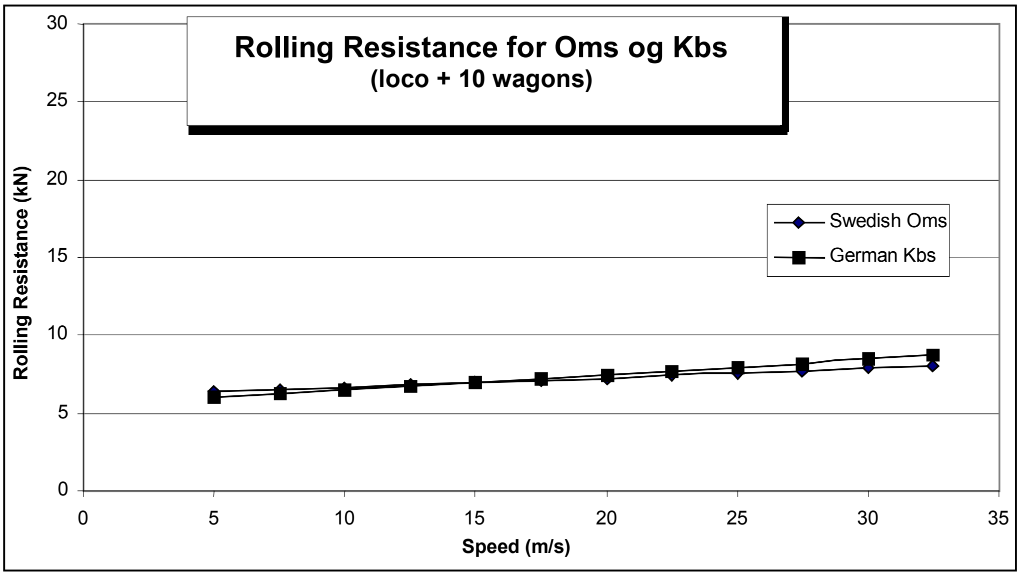


Figure 11.3 Comparison of measured (Swedish) rolling resistance and the estimated value for a locomotive and 10 empty flat cars.

The total rolling resistance shown in the figure agrees quite well for the two types of cars. For speeds between 10 and 22 m/s there is no noticeable difference. For very small speeds, under 7,5 m/s, and correspondingly high speeds, over 27,5 m/s, the difference is between 5 and 7%. For the smaller train, as in this case 10 wagons, the agreement is quite acceptable. This is in spite of the fact that there are some technical differences and two different locomotives.

For a corresponding train, in this case with 20 wagons, the calculated and measured resistances are shown in Figure 11.4.

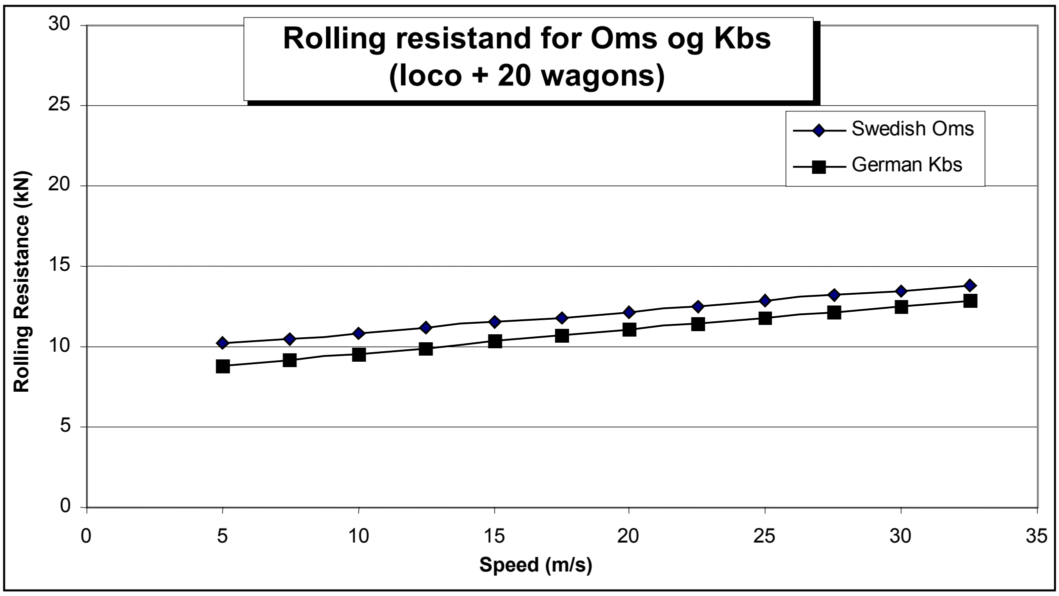


Figure 11.4 Comparison of measured (Swedish) rolling resistance and the estimated value for a locomotive and 20 empty flat cars.

The comparison is a bit different from the case with 10 wagons. Here, there resistance for the kbs-string is lower than for the Oms-string. The greatest percent wise difference is found with the lowest speeds. For speeds below 17,5 m/s the difference is between 10 and 15%. For higher speeds, 25-35 m/s, the difference is about 7-8%.

One reason for the difference is the in the Swedish Oms consideration is taken of impulse resistance in the rolling resistance. Impulse resistance is normally small and is often neglected without too much impact on the driving resistance. For the rolling resistance here in this section, if the impulse resistance were considered for the German Kbs string, the difference would be reduced to only 1-4%. So even if the impulse resistance were considered the effects on the resistance curve for the kbs-string would be negligible.

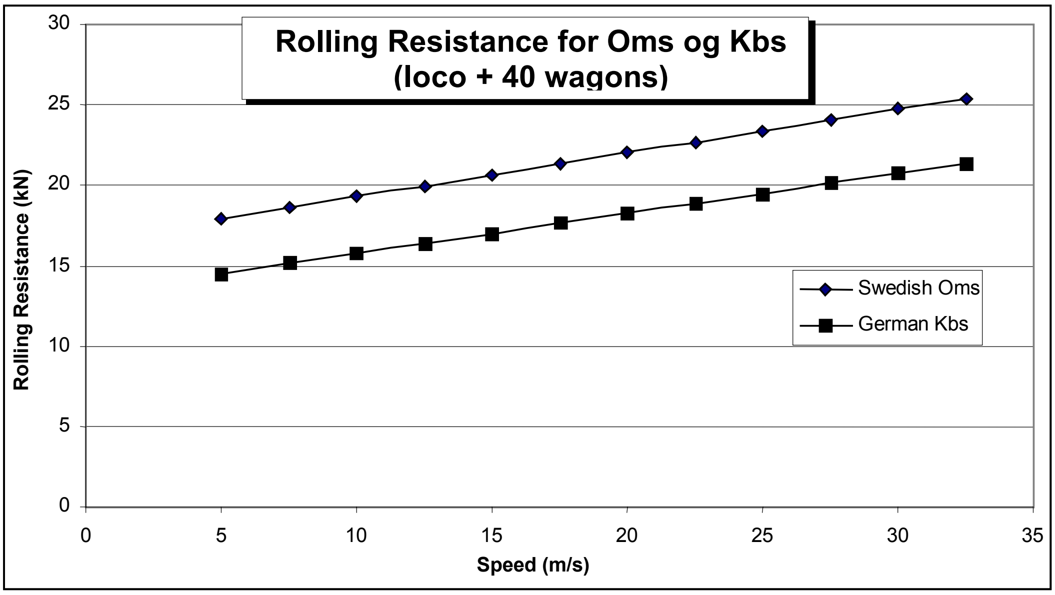


Figure 11.5 Comparison of measured (Swedish) rolling resistance and the estimated value for a locomotive and 40 empty flat cars.

For a larger train, with 40 wagons, the difference is shown in Fig. 11.5.

This figure shows the same pattern as Figure 11.4. The difference here is greater, though. For low speed the difference is 20% and falls to about 16% at higher speeds. The absolute difference is nearly constant

11.3 Relative importance of rolling resistance constants

In order to show the relation between the different terms in the equation for rolling resistance, each factor and the total are shown in Figure 11.6. The example shown is that of the kbs wagon in a string of 20 wagons. The same general trend is seen for the Oms wagon type.

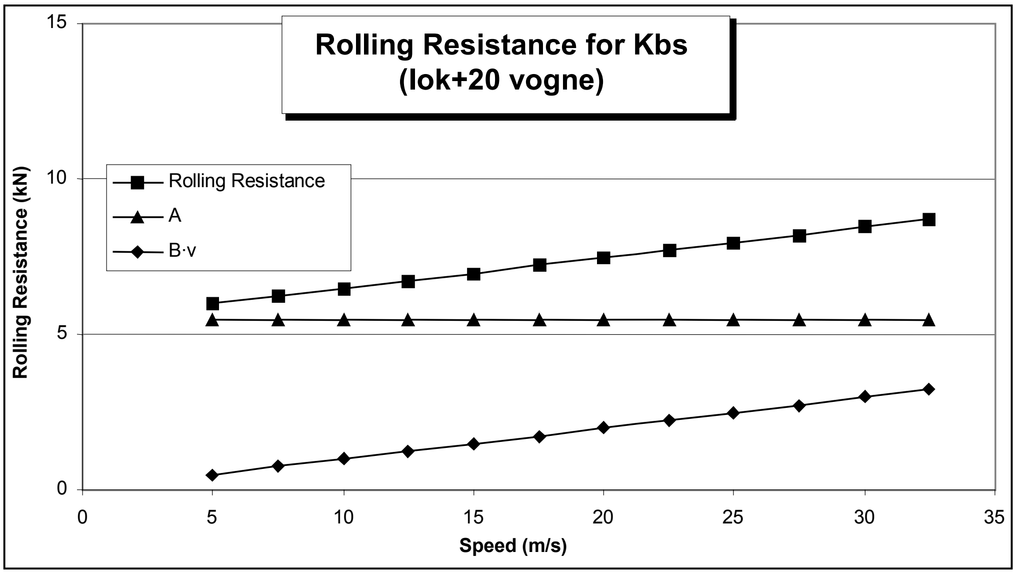


Figure 11.6 The contribution of the two terms in Equation 9.1 to the total rolling resistance for a goods train with Kbs wagons.

One can observe that:

- For speeds under 15 m/s the constant A, is the dominating factor.
- Even for a speed of 32.5 m/s (117 km/h) the speed dependent term will contribute to only about a third of the total rolling resistance.

11.4 Summary

The preceding shows that the measured and calculated values are in good agreement for shorter trains, but the difference increases to a maximum of about 20% with a train with 40 wagons. Though it should be pointed out that the trains are not identical, the wagons are of similar type, and the locomotives differ. For the purpose of general modeling of rail emissions and energy consumption, the approach should be acceptable, since it has in the lack of actual measured data, it displays correct physical tendencies and the uncertainties in wagon arrangement, traffic data *etc*. are normally larger.

12 Other operating resistance.

For a train operating on a flat straight stretch of track, there are some resistances in addition to air and rolling resistance that could be considered. Normally, though, it is these two resistances that dominate. For completeness, a short discussion is presented of two other possible resistances. They are brake disk resistance, F_{BS} and impulse resistance, F_{IMP}.

12.1 Brake disk resistance

When a train has mechanical brakes, there will unavoidably be a heating of the brake pads. This is caused by the friction against the wheels, which is the essential element of the braking process. To prevent overheating of the brake pads, locomotives and wagons are often built such that some airflow can cool the brake pads.
In Reference 1 the following equation is given for the calculation of the brake disc resistance, F_{BS}:

$$F_{BS} = n_{BS} \cdot \left(C_3 \cdot \frac{v}{v_0} + C_4 \cdot \left(\frac{v}{v_0} \right)^2 \right) \qquad (12.1)$$

Where: F_{BS} is the brake disk resistance for all brake discs on the train [N].
n_{BS} is the number of brake discs in the train (normally four per axle).
C_3 and C_4 are constants in N; C_3 = 4,33 N and C_4 = 3,16 N.
υ is the train speed in [m/s]
υ_0 is a speed constant = 27,778 [m/s]

Example: For a goods trains consisting of a six-axle locomotive and 20 wagons with four axles per wagon, at a speed of 25 m/s (90 km/h) F_{BS} is:

$$F_{BS} = 86\text{axles} \cdot 4\text{discs/axle} \cdot \left(4{,}33 \cdot \frac{25}{27{,}778} + 3{,}16 \cdot \left(\frac{25}{27{,}778} \right)^2 \right) = 555{,}26\text{N}$$

As mentioned, F_{BS} is small compared to other rolling resistances. This is emphasized by the fact that here the result is in N, while in the calculation of F_R or F_L the results are in kN at the same speed.
In Reference 3 an alternative method for the calculation of F_{BR} is presented:

$$F_{BR} = n_{BS} \cdot 0{,}014\,\text{N} \cdot \text{s}^2/\text{m}^2 \cdot \text{v}^2 \qquad (12.2)$$

Example:
Using this method (Equation 12.1) the corresponding result is:

$$F_{BS} = 86\text{axles} \cdot 0{,}014\text{N} \cdot {}^{\text{s}^2}\!/_{\text{m}^2} \cdot 25^2\ {}^{\text{m}}\!/_{\text{s}} = 645\text{N}$$

The difference between the two methods is about 16 % here. Both methods are correlations, and show that this resistance is not significant, and is therefore not included in further calculations.

<u>12.2 Impulse resistance</u>

One could consider the so-called air impulse resistance, F_{IMP} as a form of air resistance. It occurs in connection with cooling and ventilation units in locomotives and passenger wagons. For locomotives, it is primarily the cooling fan and air intake for cooling of the engine. For passenger wagons, it is the ventilation and heating/cooling equipments. The airflow occurring here is accelerated due to the motion of the train.

The air impulse resistance can be calculated from the following Equation (1) :

$$F_{IMP} = \rho \cdot Q_{luft} \cdot (\nu + \Delta\nu)$$

where: F_{IMP} is the air impulse resistance in N.
ρ is the air density - normally 1,20 kg/m^3
Q_{luft} is the airflow emanating from the train in m^3/s
υ is the train speed in m/s
υ_0 is a speed constant = 27,778 m/s (100 km/h).

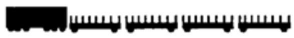
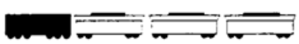
Since Q_{luft} can only be estimated in the absence of detailed technical data, an example is not shown. A estimate for a goods train locomotive is on the order of 0,1 m^3/s.

13 Driving resistance for a goods train

Since the total resistance for a goods train consists of air and rolling resistance, the information from previous chapters can be combined to give a picture of the driving resistance for several goods trains.

The basic situation is that of a straight level track. Brake and air impulse resistances are not included. The trains considered are taken from previous chapters. They are shown in the Table 13.1 below.

Table 13.1 Description of goods trains used in calculation of Chapter 13

Train	Length	Description	
Loco + 20 Sgis Full load	413,8 m	1715 t	
Loco + 20 Sgis 2/3 load	413,8 m	1302 t	
Loco + 20 Sgis 2/3 load	413,8 m	1302 t	
Loco + 20 Sgis 1/3 load	413,8 m	883 t	
Loco + 20 Sgis No load	413,8 m	475 t	
Loco + 40 Kbs Full load	579,4 m	1723 t	
Loco + 40 Kbs No load	579,4 m	623 t	
Loco + 20 Fad Full load	271,8 m	1723 t	
Loco + 20 Fad 1/2 load	271,8 m	1173 t	
Loco + 20 Fad No load	271,8 m	623 t	

13.1 Driving Resistance for litra Sgis.

Figure 13.1 shows the total driving resistance for a goods train consisting of a locomotive and 20 Sgis wagons.

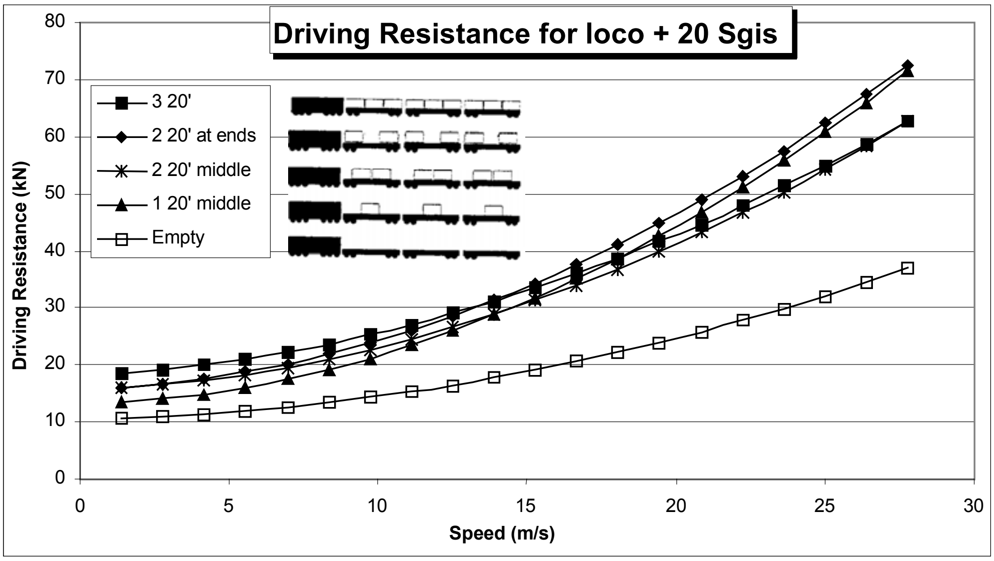


Figure 13.1 Rolling resistance for a goods train with locomotive and 20 Sgis wagons with different loading configurations.

The combination of rolling and aerodynamic resistance reduces some of the differences due to aerodynamic factors of loading, and the loaded trains all have similar driving resistance. The resistance of the unloaded train is substantially lower.

Another way to view these results is on the basis of rolling resistance per total ton of train weight. This is shown in Figure 13.2 in N/ton.

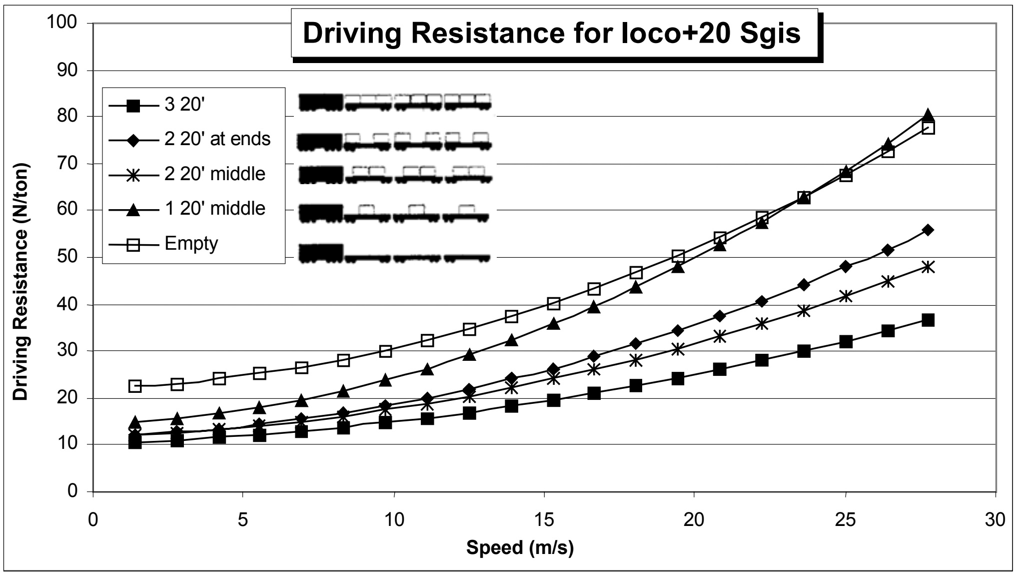


Figure 13.2 Rolling resistance per ton for a goods train with locomotive and 20 Sgis wagons with different loading configurations.

The unloaded train has the highest specific resistance. The aerodynamics are not advantageous with the empty train, and the light weight gives a high specific resistance.
For the train with 2 containers per wagon, the arrangement with the loads in the ends of the cars have about a 15% higher resistance than if the containers are placed in the middle of the wagons.
The train with one container per wagon has a high consumption, especially at speeds above 20 m/s (~72 km/h) where the aerodynamic losses are especially significant. At lower speeds, this arrangement is not too much worse than the others.

13.2 Driving Resistance for litra Fad

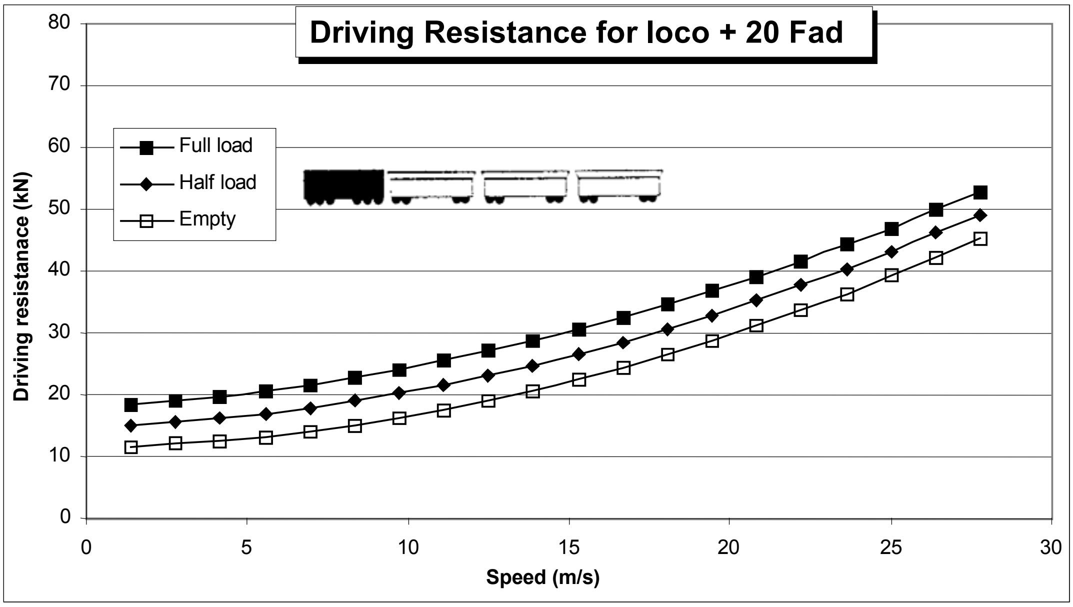


Figure 13.3 Rolling resistance for a goods train with locomotive and 20 Fad wagons with different loading configurations.

The next train considered is a goods train consisting of a locomotive and 20 litra Fad wagons. The driving resistance for three loading variations is shown in Figure 13.3.

The greatest resistance is seen for the fully loaded train. The rolling resistance plays a larger role in determining the total resistance than the aerodynamic resistance and is primarily responsible for this trend. The empty train has the smallest resistance due to its lower weight. There are some uncertainties in the air resistance for the half loaded train. The air resistance coefficient is not available directly for the half loaded trains, and was assumed to be the average of the values for the full and empty trains.

Figure 13.4 shows the resistance per ton for the train with Fad wagons. The lowest specific resistance is obtained with the fully loaded train, and the empty train has the highest specific resistance. The train with half load is about 15% higher than the fully loaded train. The aerodynamic resistance of the empty train is high, because of the possibility for the air to move in and out of the empty cars, and when divided by the low total weight of the empty train, gives a high specific resistance. The relative increase in the resistance of the empty train with high speeds emphasizes the importance of aerodynamic resistance in this case.

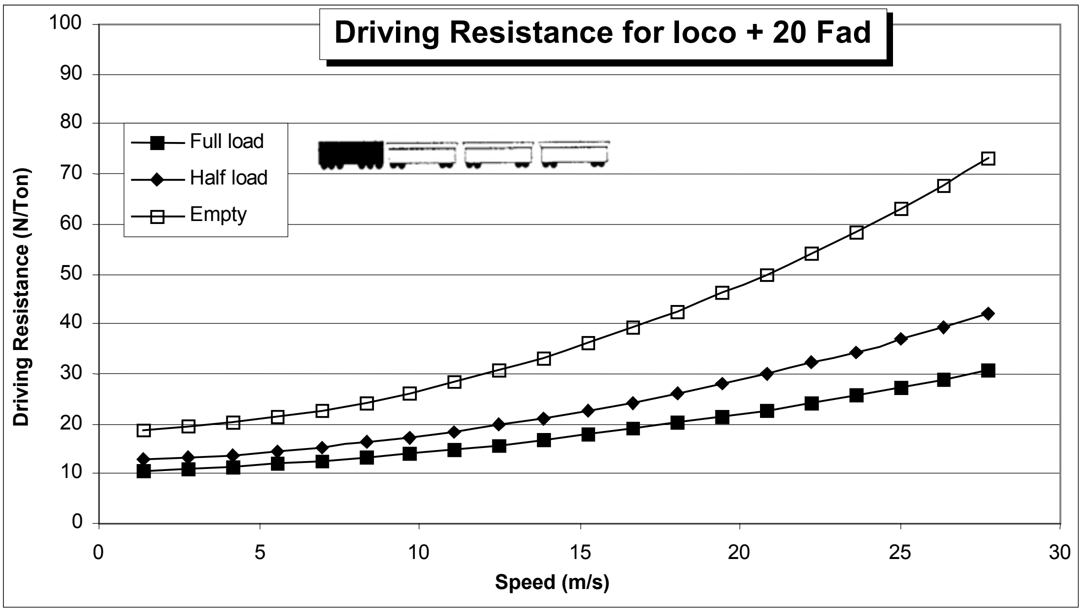


Figure 13.4 Rolling resistance per ton for a goods train with locomotive and 20 Fad wagons with different loading configurations.

13.3 Driving resistance for litra kbs

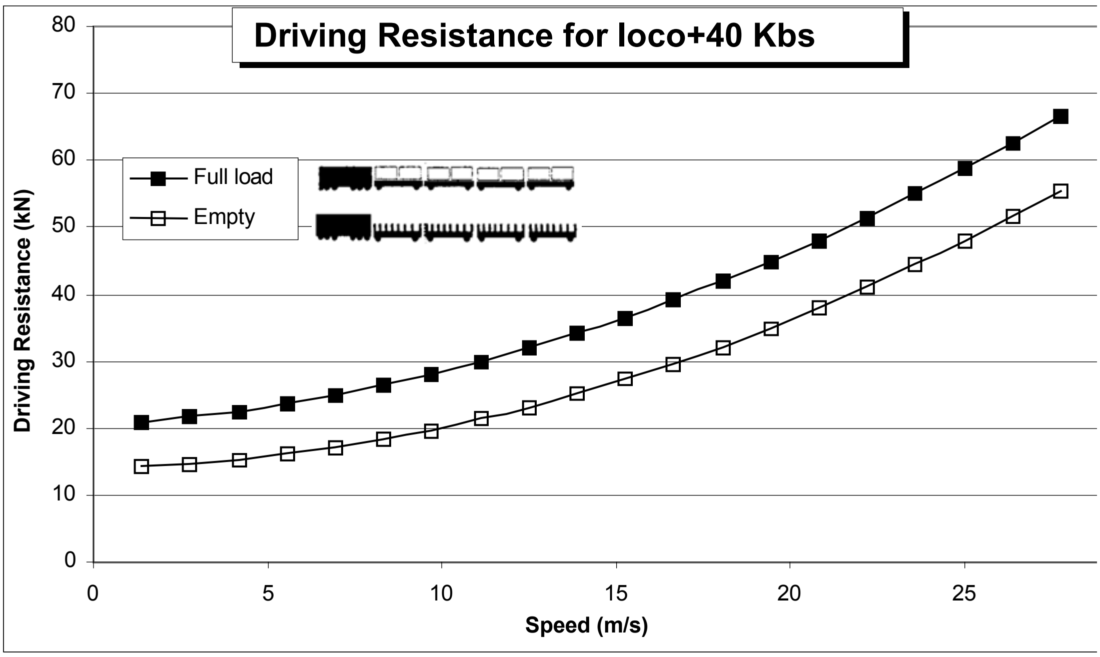


Figure 13.5 Rolling resistance for a goods train with locomotive and 40 Kbs wagons with different loading configurations.

The last example is a train consisting of two-axle wagons. In order to compare trains of similar sizes to those of the container trains in Figures 13.1 and 13.2, 40 wagons are considered instead of 20. This gives the same number of axles as the trains with four-axle wagons. The driving resistance is shown in Figure 13.5. Since data is not available for half loaded wagons, they are not considered due to the difficulty of obtaining satisfactory and reliable c_L-values.

The resistance is consistently higher for the loaded train. On the basis of train tons, the resistance can be seen in Figure 13.6, a pattern which is similar to that of the Fad-wagons.

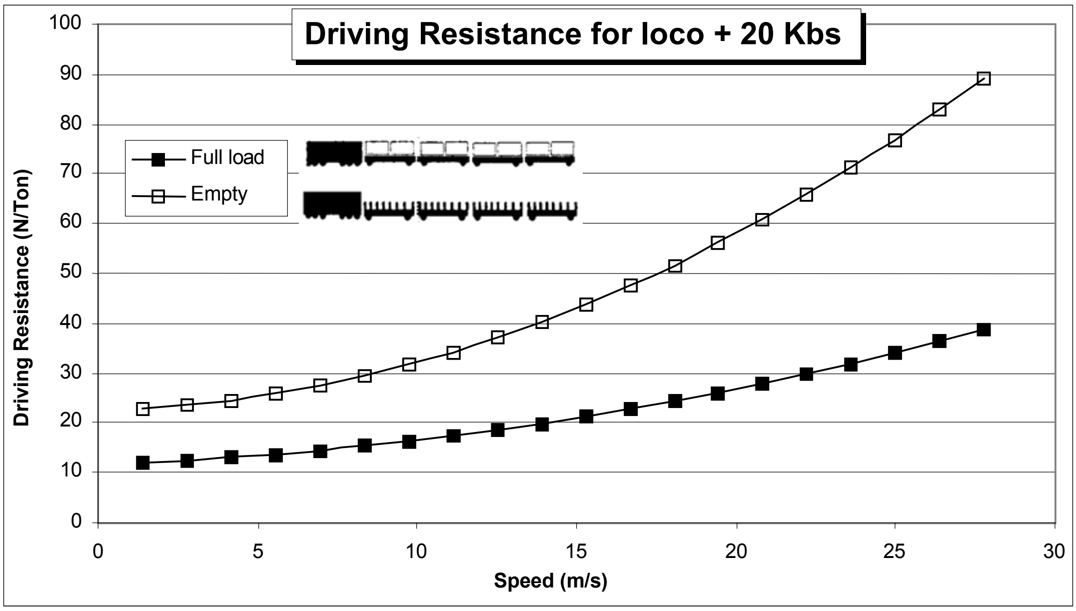


Figure 13.6 Rolling resistance per ton for a goods train with locomotive and 20 Kbs wagons with different loading configurations

The driving resistance for the train of empty wagons starts to increase markedly at about 10 m/s ~35 km/h. There is a difference of about a factor of two throughout the whole speed range, with slightly higher relative values for the highest speeds.

13.4 Relative importance of resistances

In order to illustrate the relative importance of the different driving resistances, Figure 13.7 shows the aerodynamic, rolling, and total resistances for a train consisting of a locomotive and 20 Sgis wagons with 3 containers per wagon. The train is the same as that shown in Figure 13.1 and 13.2.

Previous results showed that the total rolling resistance is relatively constant, while the aerodynamic resistance is very dependent of the speed. The dominant quantity at low speeds is the rolling resistance, and for speeds about 20 m/s (72km/h) the aerodynamic resistance takes on a more important role. Under 10 m/s, the aerodynamic resistance is negligible. At 10 m/s the aerodynamic resistance is 13% of the total resistance. For speeds between 13 and 27 m/s the aerodynamic resistance is between 20 and 40 % of the total. The aerodynamic resistance never becomes as large as the rolling resistance for this train.

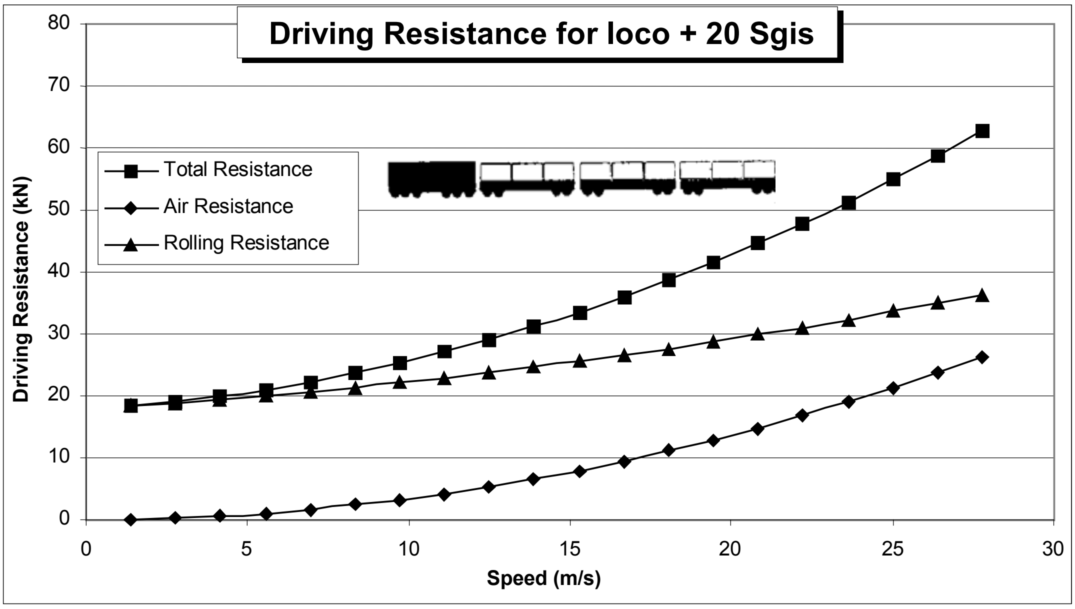


Figure 13.7 The contribution of the two terms in Equation 9.1 to the total rolling resistance for a goods train with 20 Sgis wagons and 3 containers per wagon.

This is not always the case, as shown in the example in Figure 13.8, where the driving resistance distribution is shown as a function of speed for the same trains, but in this case with only one container per wagon. Previous results indicated that this gives a larger aerodynamic loading.

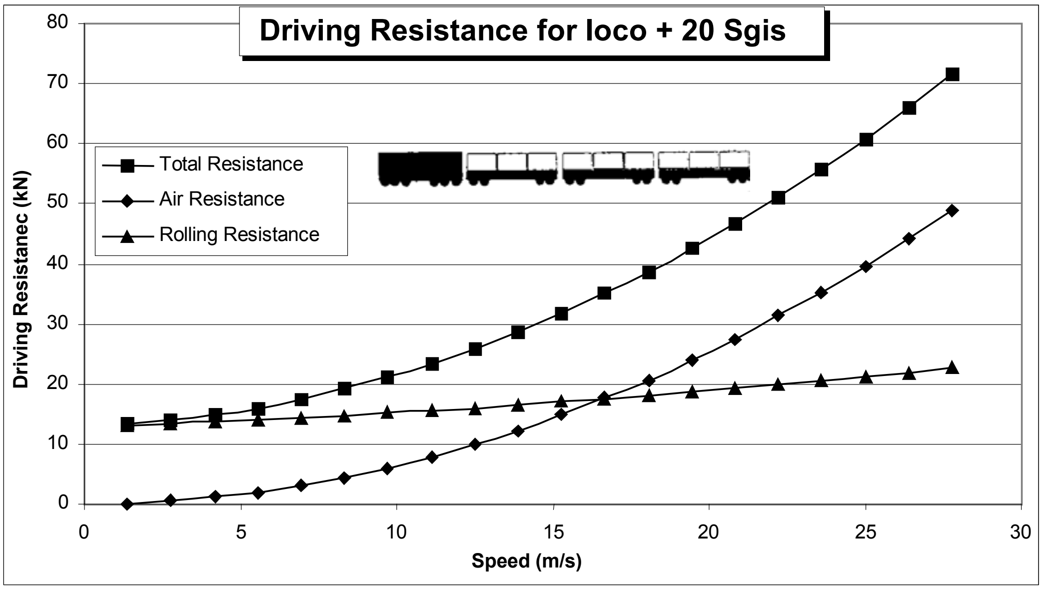


Figure 13.8 The contribution of the two terms in Equation 9.1 to the total rolling resistance for a goods train with 20 Sgis wagons and one container per wagon.

In this case, the train is lighter, which reduces the rolling resistance. In addition to that, the aerodynamic load in increases by the nature of the load, on one container per wagon. This results in a different trend than for the results of the previous figure.

Already at a speed of 17 m/s the aerodynamic and rolling resistances are equal, and above that speed, the aerodynamic resistance becomes dominant. Only for the very lowest speeds, does the aerodynamic resistance become an insignificant fraction of the total resistance.

Notice than in both cases, the total resistance is similar, 18-20 kN at about 5 m/s and 55-60 kN at 25 m/s. Though the total is similar, the results show the different factors determining the distribution of the resistances. This is a fortunate situation, since this compensation reduces the sensitivity of the estimation of the driving resistance and energy consumption to the specific train configuration. This latter information is normally not available when inventory studies are being conducted.

14 Proposals for improvement

In the preceding chapters the air, rolling and total resistances for a variety of goods trains have been investigated. Based on this, it is now possible to make an analysis of improvements in train performance as indicated by the chapter on aerodynamic resistance. The possibilities investigated are the covering empty wagon as well as a better utilization of container wagons.

14.1 Improvements for Sgis.

As mentioned in the chapter on aerodynamic resistance, this type of wagon can be loaded in different way. Regarding the aerodynamic resistance some of these are better than others. In the first case, a train consisting of 20 wagons with two containers per wagon is examined. Figure 14.1 shows the total driving resistance for such a train with the containers in the ends or in the middle.
There is an addition improvement opportunity, which is to place an empty container on the wagon, such that there are three containers on the wagon. The idea here is to improve the aerodynamic situation without significantly increasing the weight (rolling resistance).

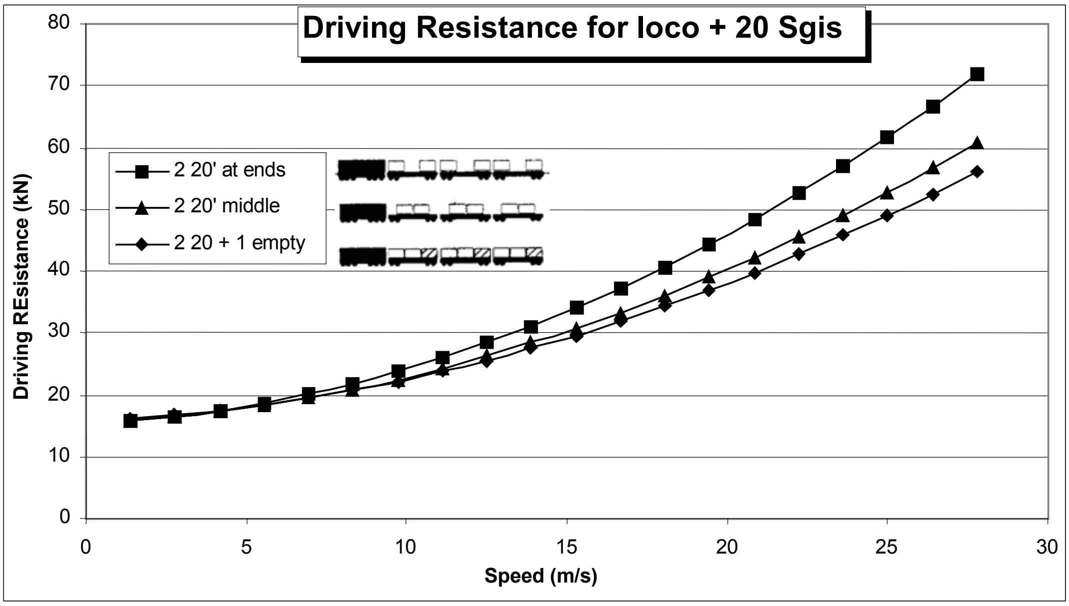


Figure 14.1 The effect carrying an empty container on driving resistance for a with 20 Sgis wagons and two loaded containers

Both F_R and F_L will change. F_R will increase due to the weight of the extra container. This will be limited, since an empty container weighs about 2,3 tons (Appendix 1). On the other hand, the aerodynamic resistance will fall since the large spaces between the containers will now be full. The value of c_L will then fall from 0,392 and 0,276 to 0,218. The question is, whether the air resistance falls enough to make a significant reduction in the total driving resistance. The result is shown in Figure 14.1:

The largest driving resistance is obtained if the two containers are placed in the ends of the wagon. The resistance then is lower if they are placed in the middle, analogous

to Fig. 4.8 (c_L A), since F_R is the same. The improvement with the extra container gives a reduction in driving resistance of 22 and 8% respectively at a speed of 27,77 m/s (100 km/h). For speeds below 11 m/s (40 km/h) the reduction can no longer be seen if the containers are placed in the middle. On the other hand, a reduction in resistance of 8% can be achieved relative to the placement of the containers in the ends of the wagon.
There is a potential reduction in driving resistance by placing an empty container on the car in order to achieve a better aerodynamic situation. This reduction would give a better result in situations where the trains run long stretches without stopping, where acceleration resistance is less important to overall energy consumption.

Next, the case is considered where there is only one container per wagon. Here the proposal is to place two empty containers on each wagon, such that the same aerodynamic conditions are achieved as shown in Figure 14a. The result is shown in Figure 14.2.

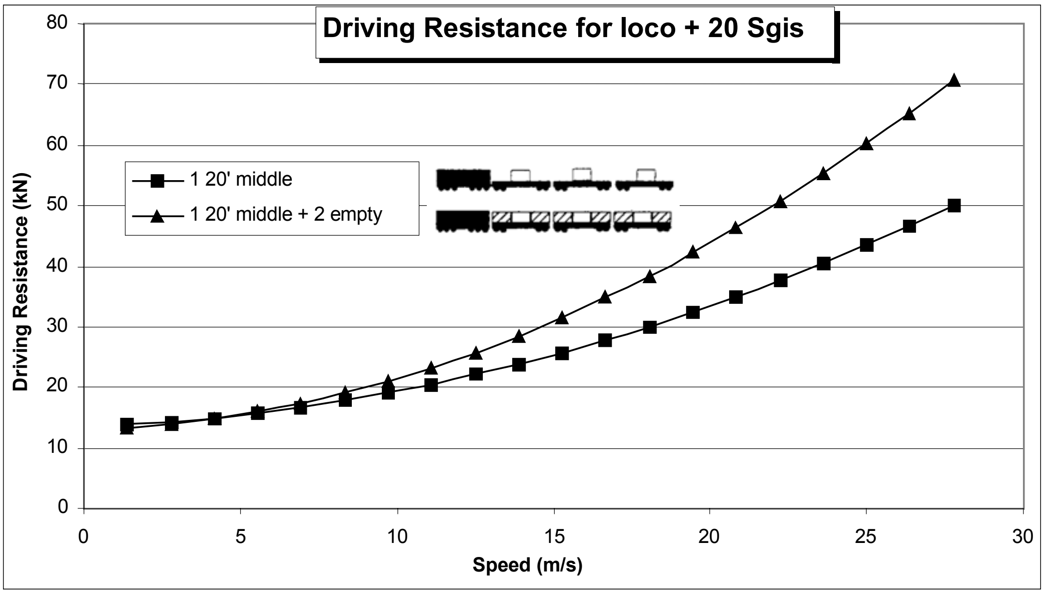


Figure 14.2 The effect carrying an empty container on driving resistance for a with 20 Sgis wagons and one loaded container.

There is also a significant reduction to be found. The two extra containers weigh a total of 4,6 tons. Nonetheless, a reduction of about 30% is achieved at a speed of 27,77 m/s (=100 km/h). This again is due to a reduction in c_L, which falls from 0,452 to 0,218. In this case the aerodynamic resistance is halved, but the rolling resistance increases by about 6%. Again, the advantage is only shown for speed over about 10 m/s.
In principle then, a significant improvement in the driving resistance on non-fully loaded container wagons can be achieved by carrying empty containers, thus improving the aerodynamic characteristics of the loaded wagons. This advantage must be weighed against factors such as steadiness of the driving characteristic, extra time and cost for loading, logistics, *et*c.

14.2 Improvements for Fad

For Bulk goods wagons litra Fad the conditions are simpler than for the Sgis.

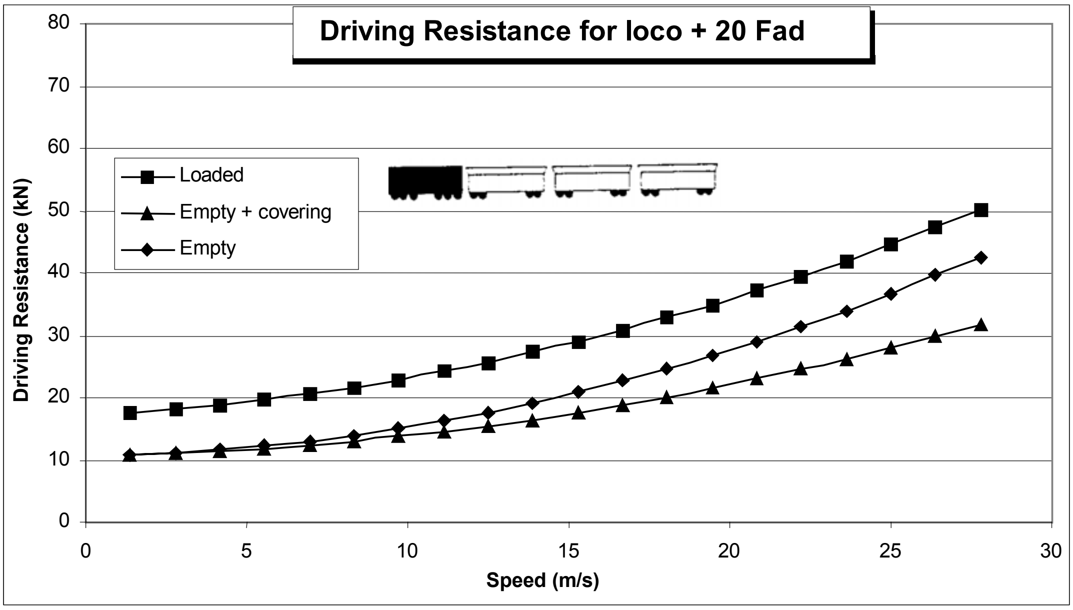


Figure 14.3 The effect covering empty wagons on driving resistance for a with 20 Fad wagons.

Potential improvements would be by covering the wagons when empty, either with some kind of plate or a tarpaulin. In both cases, there would only be a minimum increase in weight, and improvement would be due to a reduction in aerodynamic resistance from flow in and out of the empty wagons. The results are shown in Figure 14.3.

The results show a significant reduction in the driving resistance, and for a speed of 27,77 m/s (100 km/h) the estimated reduction in resistance is about 25%. Below 10 m/s (36 km/h) there is no noticeable difference. It can also be seen that at higher speeds, the driving resistance for the empty train approaches that of the loaded. At higher speeds, it is possible that the resistance of an empty train could be greater than that of a fully loaded train.

14.3 Improvements for Eaos

As a final example, a litra Eaos is chosen (see figur 14.4). As was the case for the litra Fad the idea is to reduce the aerodynamic resistance by covering the empty gondola with a cover or tarpaulin.

The figure shows significant savings for the empty cars can be achieved by covering them to improve aerodynamics. A reduction in driving resistance of about 25 % is projected at a speed of 27,77 m/s. At speeds below 8 m/s (30km/h) there is not a noticeable difference. In this case, driving resistance of the empty train is projected to be greater than that of the loaded train at speeds over about 21 m/s.

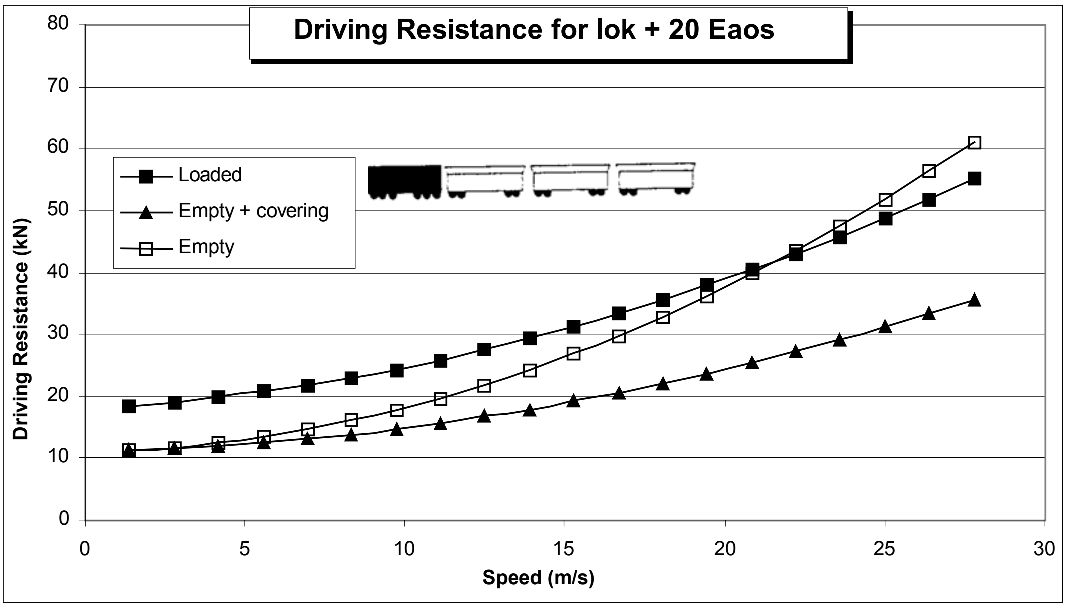


Figure 14.4 The effect covering empty wagons on driving resistance for a with 20 Fad wagons.

15 Driving resistance as a function of goods loading.

In the chapters on air and rolling resistance, goods trains with different loads were analyzed. The difference here was often how many containers that were loaded on each wagon, and how they were located. The assumption was that all containers were loaded such that each wagon achieved the axle loading of 20 tons per axle, the capacity of the wagons.

Actually, conditions are not as sharply defined, and the load from container can vary considerably, just as long as the axle capacity is not compromised. The idea of the following is to show the difference in driving resistance with different loadings

To reduce complexity, only one goods train is examined. The train, the same as in discussions of driving resistance, consists of a diesel locomotive, (MZ4) and 20 4-axle wagons, (Sgis). 12 conditions were considered: 3, 2 or 1 container per wagon, each of which could be loaded with a weight of 100, 50 or 33 % of the maximum, as well as empty. With 100% load, the container is not necessarily full, but that it is loaded to provide an axle load of 20 ton. Since this type of wagon can accept a maximum load of 62 tons, each container, including load can weigh 62/3 = 20,5 tons.

Generally, it can be said that the driving resistance that the rolling resistance is dependent on the total weight of the train, while the aerodynamic resistance is dependent on who the containers are placed on the wagons. The principle is shown in Figure 15.1.

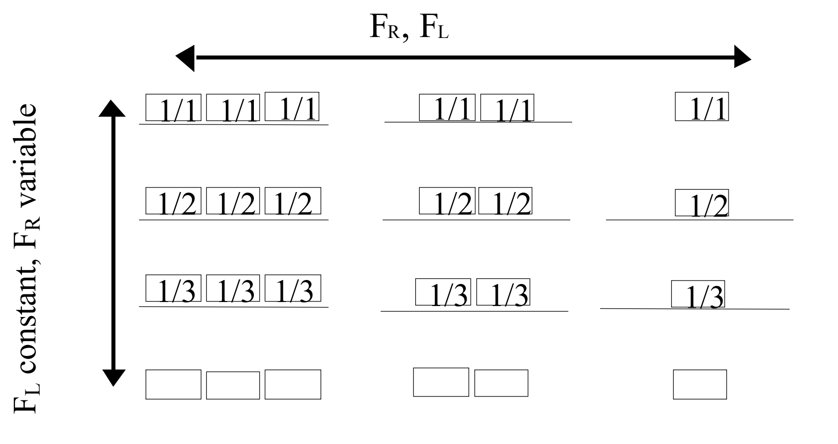


Figure 15.1 Schematic view of container loading and placement on rolling and aerodynamic resistance.

When the number of containers and their load is changed, both there air and rolling resistance will change. But F_L will be constant if the number of containers and their placement are maintained, which means that only F_R will vary.

<u>15.1 Driving Resistance for Sgis</u>

The driving resistance in kN is shown in Figure 15.2 for a goods train with 3 containers each on a total of 20 wagons.

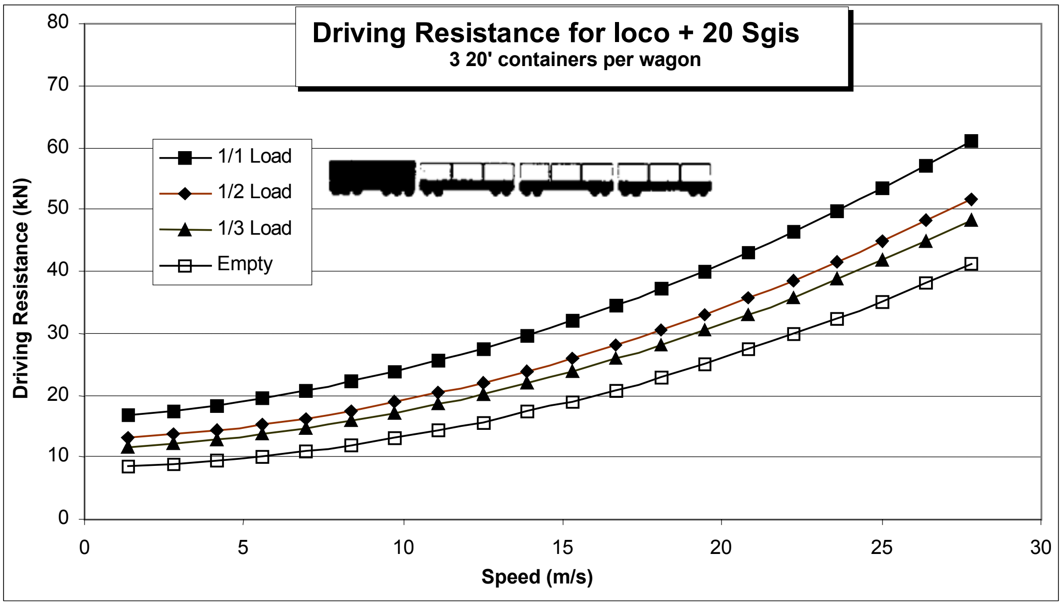


Figure 15.2 The effect of container contents (weight) on the total driving resistance of a train with 20 Sgis wagons, 3 containers per wagon.

The resistance for the fully loaded train is the largest, while the unloaded trainhas the lowest, about 30% lower than the fully loaded. Therefore, there is a noticeable difference as to whether the containers are empty or full, while there is little difference in the medium loading range, probably experienced frequently in practice.

As before, it is of interest to show the resistance on a mass basis, in this case, based on the total train weight, that is, in N/ton. The first case is for a train with 3 containers per wagon and the resistance is shown in Figure 15.3.

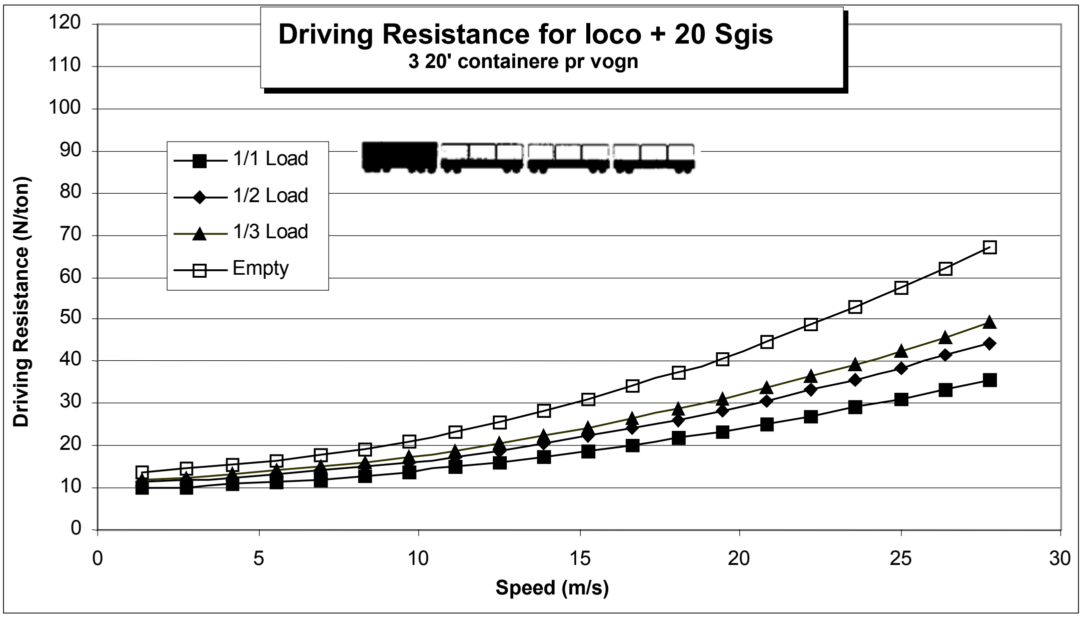


Figure 15.3 The effect of container contents (weight) on the weight specific driving resistance of a train with 20 Sgis wagons, 3 containers per wagon.

The driving resistance for the same goods trains with two containers per wagon is shown in Figure 15.4:

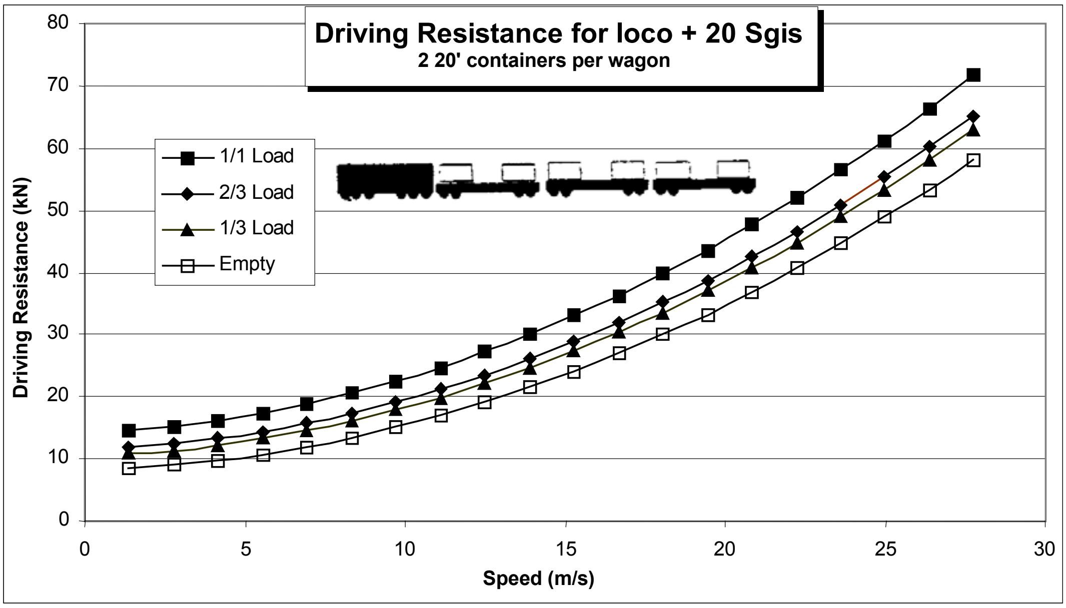


Figure 15.4 The effect of container contents (weight) on the total driving resistance of a train with 20 Sgis wagons, 2 containers per wagon.

If Figures 15.2 and 15.4 are compared, it can be seen that the relative effects of the amount of loading are greatest for the light loads. The full load resistances are similar. Since the train only has 2/3 of the resistance with 3 containers per wagon, the rolling resistance in correspondingly less. On the other hand, the air resistance F_L (see Chapters 4 and 5) is significantly higher due to the placement of the containers. It can also be seen that the driving resistance is nearly the same at low speed, which is where the rolling resistance F_R, dominates. Correspondingly, the difference is greater at the higher speeds, where F_L dominates. Both Figure 15.2 and 15.4 show the same general pattern, but the individual differences are less in Figure 15.4 due to relative differences in aerodynamic resistance.

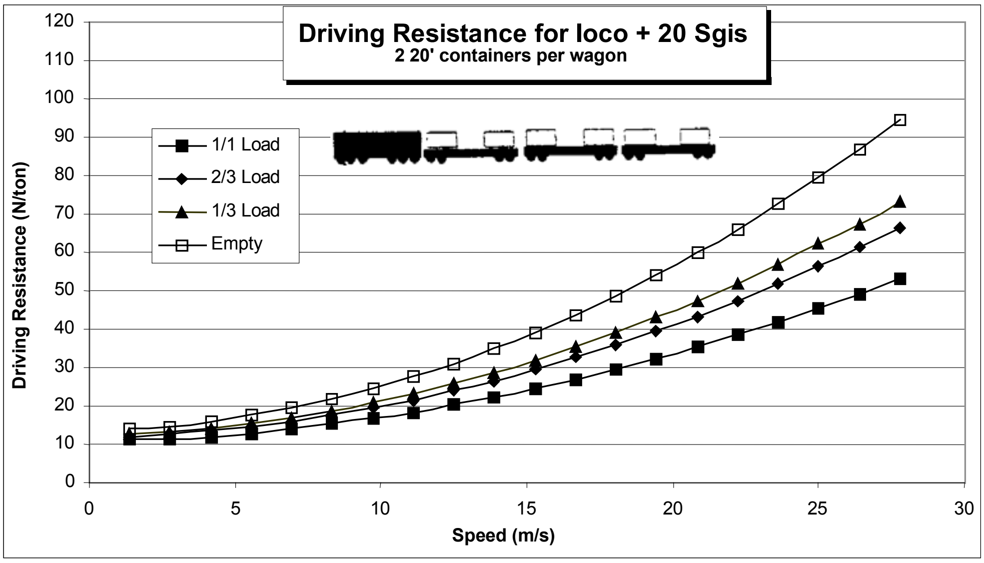


Figure 15.5 The effect of container contents (weight) on the weight specific driving resistance of a train with 20 Sgis wagons, 2 containers per wagon.

The driving resistance in N/ton is shown for a train with 2 containers per wagon in Figure 15.5. If Figures 15.3 and 15.5 are compared, one sees that the curves follow the same general pattern as previously discussed. The resistance per ton is lower for the train with 3 containers (Figure 15.3) since the lower base resistance due to lower aerodynamic resistance, is divided by a greater weight, since the capacity is larger with three containers instead of 2.

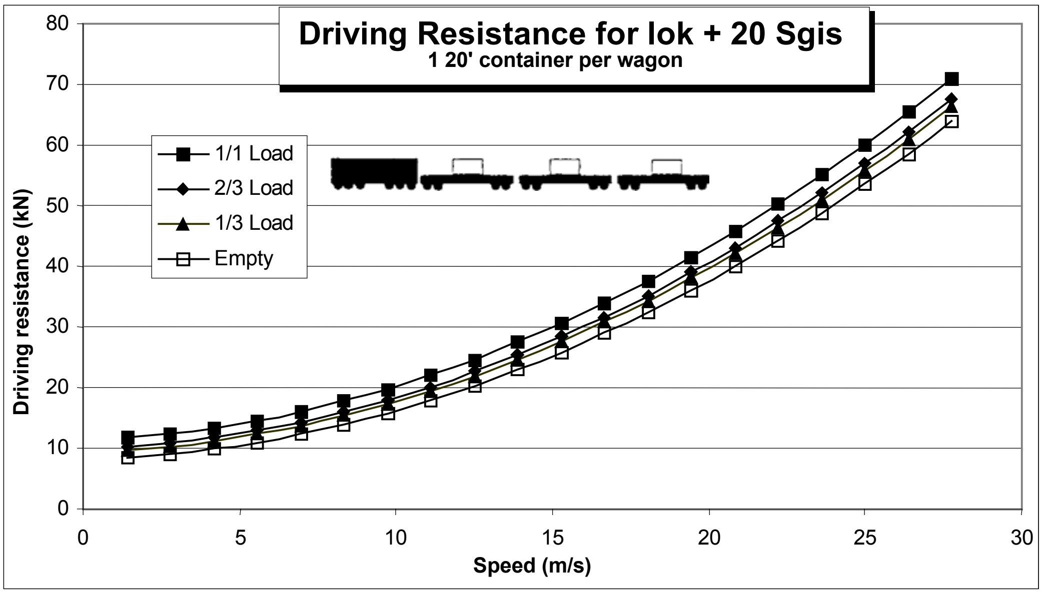


Figure 15.6 The effect of container contents (weight) on the total driving resistance of a train with 20 Sgis wagons, 1 container per wagon.

Qualitatively similar results are seen in Figures 15.6 and 15.7, where the resistance is shown for a train with one container per wagon. The difference between the full and empty trains are much smaller than for the cases with 2 or 3 containers, since the fully loaded train with one container weighs about the same as the 3 container train with one third load.

Resistance per ton, shown in Figure 15.7, is quite a bit higher for the one container train than for the three container per car train, as the aerodynamic resistance is highest and the load lowest when there is only one container per car.

In terms of modeling of goods transport, these results are of interest, in that on a resistance per ton, these trains give a reasonably estimate of what could be expected for trains from a fully loaded, aerodynamically effective, fully loaded train (3 containers, full) to and aerodynamically ineffective, empty train (1 container, empty). Figure 15.8 summarizes the span in weight specific loading for the trains shown previously in this chapter. In practice, it is reasonable to assume that actual trains lie somewhere between these two extremes. For low speeds, where aerodynamics are not important, there is little difference between any of the trains. At 25 m/s, the median value is 59 N/ton, with the high value being 89 for the empty train with one container and the low 31 for the full train with 3 containers. This can be considered a sort of worst-case situation, with a difference on the order of ± 50% in practice the variation would be smaller, since completely empty trains or completely loaded trains are not the norm for goods traffic.

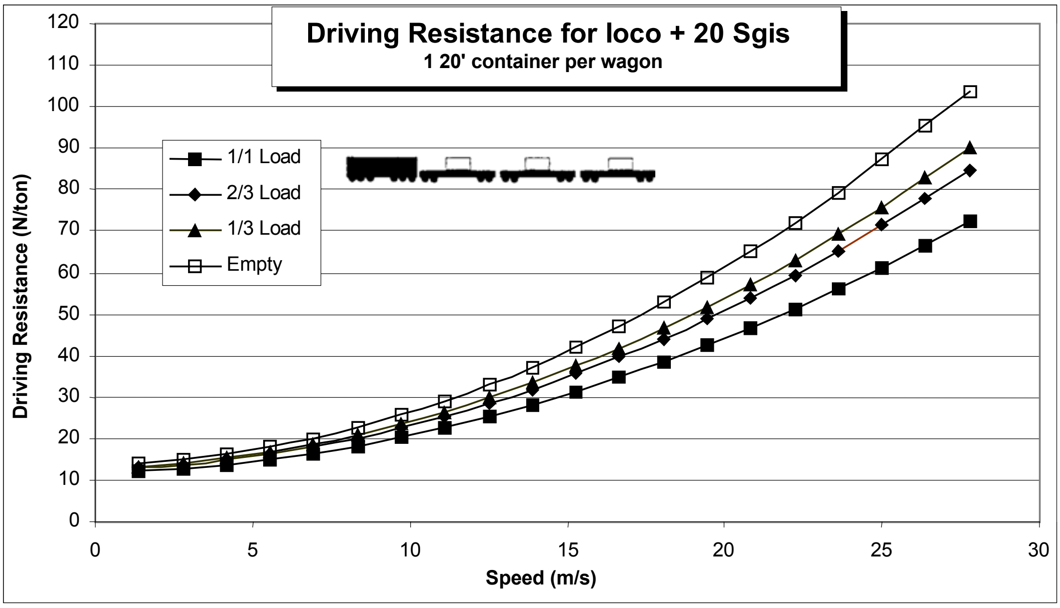


Figure 15.7 The effect of container contents (weight) on the weight specific driving resistance of a train with 20 Sgis wagons, 1 container per wagon.

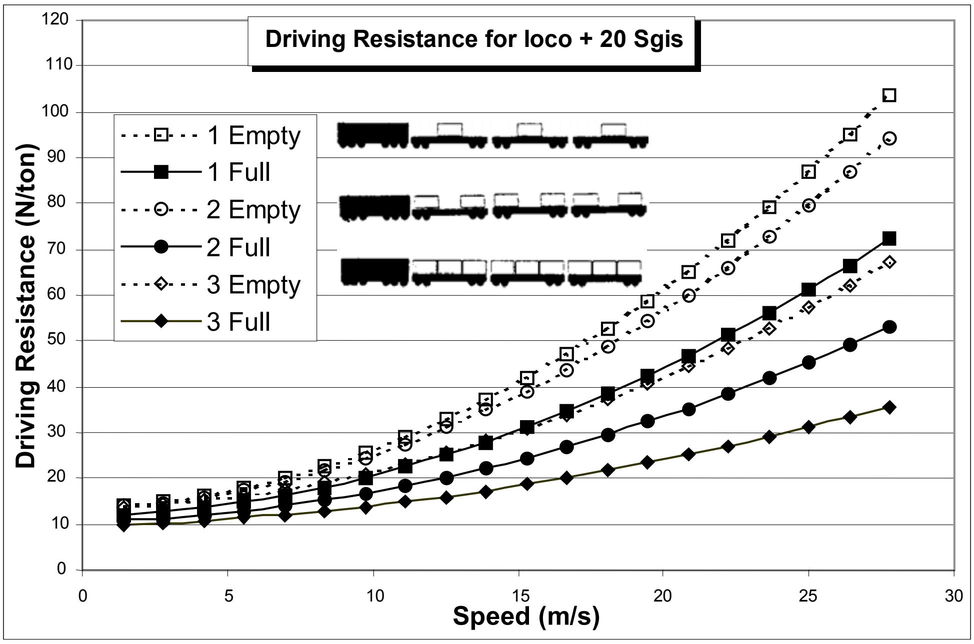


Figure 15.8 The effect of container contents (weight) on the weight specific driving resistance of a train with 20 Sgis wagons, 1, 2, or 3 container per wagon.

16 Passenger Trains and Simplified Goods trains

16.1 General passenger trains

The calculations for passenger trains are basically the same as for goods trains. Here, the wagons are basically all the same shape, so the difference in heights does not enter into consideration. From the method of (3) the aerodynamic resistance can be calculated. The air resistance coefficient can be calculated:

$$F_{L,tot} = \frac{\rho}{2}(c_{L,loco} + c_{L,1} + (n-2)c_{L,m} + c_{L,n}) \cdot A_{norm} v^2 \qquad (16.1)$$

Where: $F_{L,tot}$ is the total aerodynamic resistance of the train
$c_{L,loco}$ is the drag coefficient for the locomotive
$c_{L,1}$ is the drag coefficient for the first wagon after the locomotive
$c_{L,m}$ is the drag coefficient contribution for the intermediate wagons
$c_{L,n}$ is the drag coefficient for the last wagon in the train

Reference (3) recommends the following values for an IC train with a type 103 locomotive, typical of intercity and regional locomotive drawn trains:
$c_{L,loco} = 0,3$
$c_{L,1} = 0,23$
$c_{L,m} = 0,14$
$c_{L,n} = 0,3$

The method can also be used for goods trains, though not as detailed as the method presented in previous chapters. The value of $c_{L,m}$ is said to range from 0,15 to 0,3 for goods trains.

For a high-speed train, the following formula is used:

$$F_{L,tot} = \frac{\rho}{2}(c_{L,0} + n \cdot c_{L,m}) \cdot A_{norm} v^2 \qquad (16.2)$$

where: $c_{L,0} = 2*0,2 = 0,4$ and $c_{L,m} = 0,095$

The rolling resistance coefficient is said to lie between 0,001 and 0,003

16.2 Comparison of different train types.

Table 6.1 shows a comparison of the product of the normalized frontal area and the drag coefficient for a high speed train using Equation 16.2, a classical locomotive drawn regional train, and a homogeneous goods train, with the closed wagon type Gls, the closed type of wagon to a passenger train. The trains are compared at equal lengths. As might be expected, the TGV train has the lowest aerodynamic resistance, since it is specially designed for the high-speed operation. The classical regional train has the next highest. It is still lower than the goods train with a homogeneous

C_L*A_{Norm}	Train Length	
Train Type	200m	400m
Homogeneous Goods MZ + type Gls	24.6	39.8
Danish Regional MZ + type Bn	15.3	27.9
TGV Duplex	11.6	21.1

Table 16.1 Comparison of estimated aerodynamic resistance parameter for different kinds of trains.

arrangement of closed boxcars, since there is usually a connector of some sort for walking between two wagons. This reduces aerodynamic losses between two cars.

An additional correlation for the total driving resistance of high speeds trains can be found in Reference (7):

$$F_{tot} = 2540 + 120{,}4 \cdot v + 7{,}413 \cdot v^2 \qquad (16.3)$$

where:

F_{tot} is the total driving resistance in N
v is the speed in m/s

16.3 Resistance for Train Sets

For the train set, the total driving resistance is often a function of the speed. A typical function to describe this is given in Equation 16.4:

$$F_{tot} = A + B \cdot v + C \cdot v^2 \qquad (16.4)$$

where: A, B and C are constants that depend of the equipment
v is the speed in m/s

All constants are given from Reference 4. The constants depend partially on the characteristics of the equipment, but also on how many train sets are included in the train. For example, ER and MF have lower driving resistance with more sets in the train. This is due to better aerodynamics as the length of the train is increases. The large areas at the ends have less relative importance.

Equation 16.4 is not of the form of resistance coefficient, as is normally used. The first term is primarily due to rolling resistance and the last term is correspondingly related to the aerodynamic resistance. The values can then be converted to the resistance coefficients C_R and C_L.

16.3.1 Calculation of driving resistance for MF:

First, the resistance coefficient is calculated for MF and ER. From this, the air resistance drag coefficient can be calculated. The expression is derived on the basis of measured resistance values provided by Reference 4.

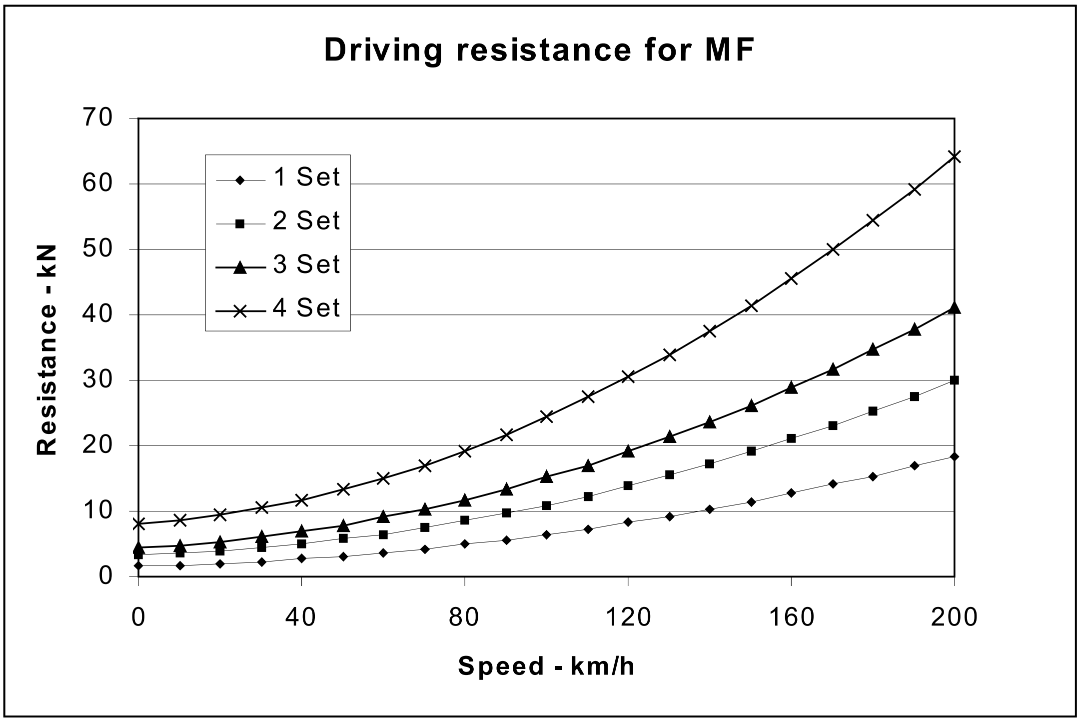


Figure 16.1 Driving resistance for MF as a function of speed

Expressions are available for one, two, three and five coupled MF sets. On the other hand, there are only values available for one ER set. This means that the resistance expressions for several coupled train set must somehow be calculated from the given values. This is possible since the ER and MF are built of the same basis wagon parts. The difference is basically that there is a wagon more in the ER than in the MF. If the resistance from the pantographs of the ER and the exhaust of the MF are assumed to be of similar magnitude, then the resistance per wagon can be assumed equal for both types.
First, the resistance values are check for the MF. The following expressions are for up to 5 sets coupled together (4).

$$
\begin{aligned}
&1\text{ set}: F_{tot} = 1620 + 47{,}16 \cdot v + 4{,}575 \cdot v^2 \\
&2\text{ sets}: F_{tot} = 3210 + 78{,}48 \cdot v + 7.232 \cdot v^2 \\
&3\text{ sets}: F_{tot} = 4480 + 109{,}44 \cdot v + 9{,}888 \cdot v^2 \\
&5\text{ sets}: F_{tot} = 7958 + 171{,}8 \cdot v + 15{,}16 \cdot v^2
\end{aligned}
\qquad (16.5)
$$

For Force in N, v in m/s

Figure 16.1 shows the total driving resistance for the different numbers of train sets in the total train.

16.3.2 Calculation of driving resistance for ER:

For this type of train there is a correlation available for the total driving resistance with one train set with the speed in km/h as the independent variable (4):

$$F_{tot} = 2503 + 19{,}93 \cdot v + 0{,}53 \cdot v^2 \qquad (16.6)$$

Though there is only a relationship for one set, it is possible to approximate values for larger sets. Since the MF and ER have wagons of about the same length, and approximate resistance value can be found by assuming that the driving resistance given in Equation 16.5 increases linearly with the number of wagons. It is assumed that the expression is valid for both types. Then by using Equations 16.5 and 16.6, the constants A, B C in Equation 16.4 can be found as a function of train length:

$$\begin{aligned} A &= 0{,}0454 \cdot L_{train} + 1{,}936 \\ B &= 0{,}53 \cdot L_{train} + 16{,}06 \qquad (16.7) \\ C &= 26{,}95 \cdot L_{train} + 39{,}73 \end{aligned}$$

The results for MF and ER are shown in tables 16.2 and 16.3 below. Values are calculated for up to the maximum number, five, of couple train sets.

Results for MF:

No. of sets	1set	2set	3set	4 set	5 set
Length	58.8	117.6	176.4	235.2	294
A	1624.27	3208.81	4793.36	6377.9	7962.4
B	47.2	78.38	109.5	140.7	171.9
C	4.603	7.271	9.938	12.605	15.272
C_L	0.680	1.075	1.469	1.863	2.258
C_R	1.75E-03	1.73E-03	1.72E-03	1.71E-03	1.71E-03

Table 16.2 Driving resistance parameters of the MF train with multiple sets.

C_L is calculated from C, and C_R from A and B

Results for ER:

No. of sets	1set	2set	3set	4 set	5 set
Length	76.53	153.1	229.6	306.1	382.6
A	2102.1	4164.4	6226.7	8289.1	10351.4
B	56.61	97.17	137.7	178.3	218.8
C	5.408	8.879	12.35	15.82	19.29
C_L	0.799	1.312	1.826	2.339	2.852
C_R	1.65E-03	1.63E-03	1.62E-03	1.62E-03	1.62E-03

Table 16.3 Driving resistance parameters of the ER train with multiple sets.

C_R is nearly constant regardless of the number of train sets, as would be expected. C_L, appears unusual. Figures 16.2 and 16.3 show the total resistance for trains consisting of from one to five sets of MF and ER trains.

16.3.3 Calculation of driving resistance for MR:

The resistance value for an MR train can also be found in this way. The results are given in Newtons in the following equation with speed in m/s.

$$F_{tot} = 2503 + 19{,}93 \cdot v + 0{,}53 + v^2 \qquad \text{(A5.5)}$$

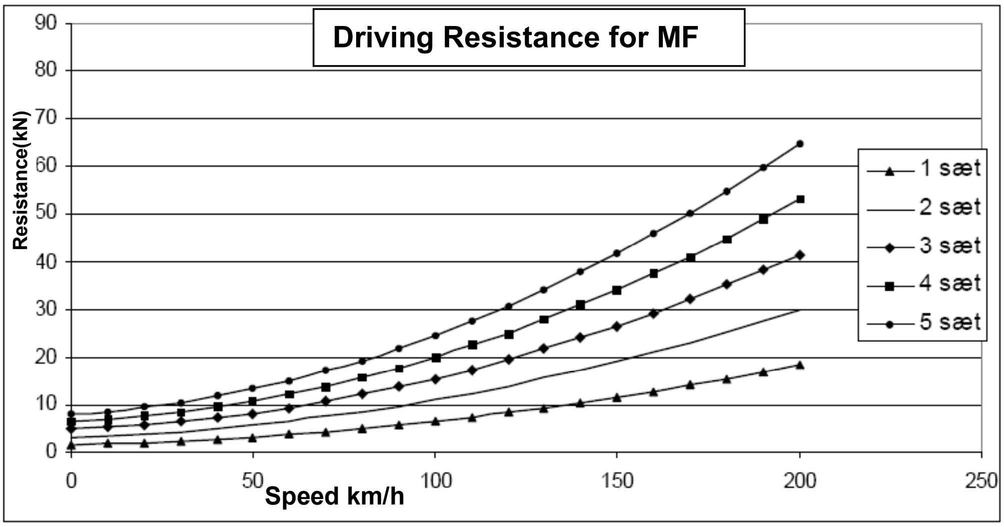


Figure 16.2 Driving resistance for trains with multiple MF sets

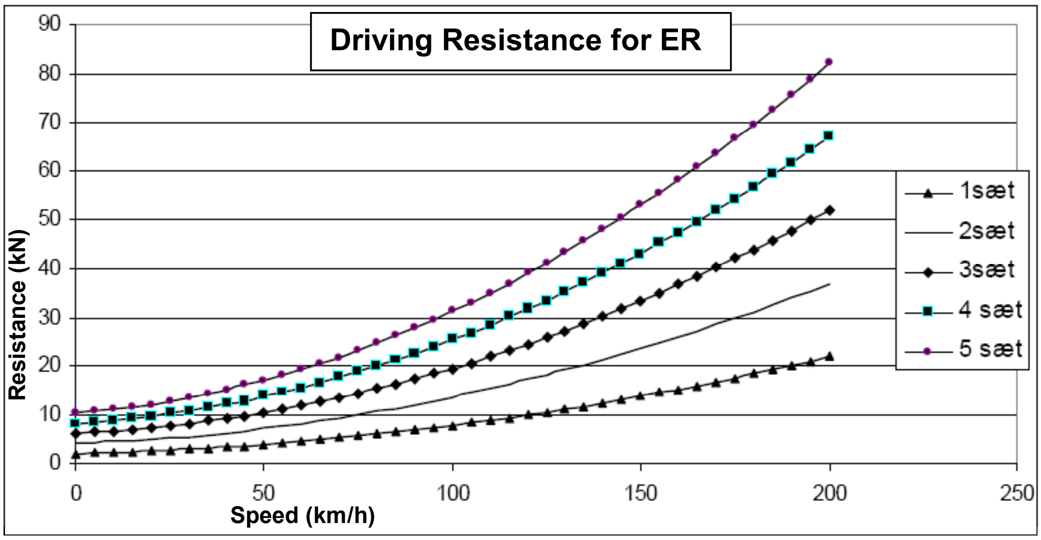


Figure 16.3 Driving resistance for trains with multiple ER sets

The resistance values for one MR set are given in (8) to be:

$$C_R = 0{,}002 \text{ and } C_L = 0{,}967$$

There are no values in the literature for multiple sets, and the structure does not make it reasonable to calculate in the same fashion as for the MR or ER.

As with the ME and ER, C_R is assumed to be constant. C_L is calculated as is there was only one train string. This will give a reasonable value. The first set is calculated as above, then each wagon, (a set consists of two motor wagons) as a normal wagon with a CL value of 0,15. This value was chosen instead of 0,11 for a normal passenger wagon, since the MR has a space between the train seta, as well as airflow from exhaust and ventilation, which cause further aerodynamic losses. With these assumptions, the resistance numbers for up to 5 sets couple together are given in 16.4. and the results shown in graphical form in Figure 16.4 for up to 5 sets coupled together.

No. of sets	1 set	2 set	3 set	4 set	5 set
Length	44.68	89.36	134.04	178.72	223.4
C_L	0.967	1.267	1.567	1.867	2.167
C_R	2.00E-03	2.00E-03	2.00E-03	2.00E-03	2.00E-03

Table 16.4 Driving resistance parameters for multiple MR train sets.

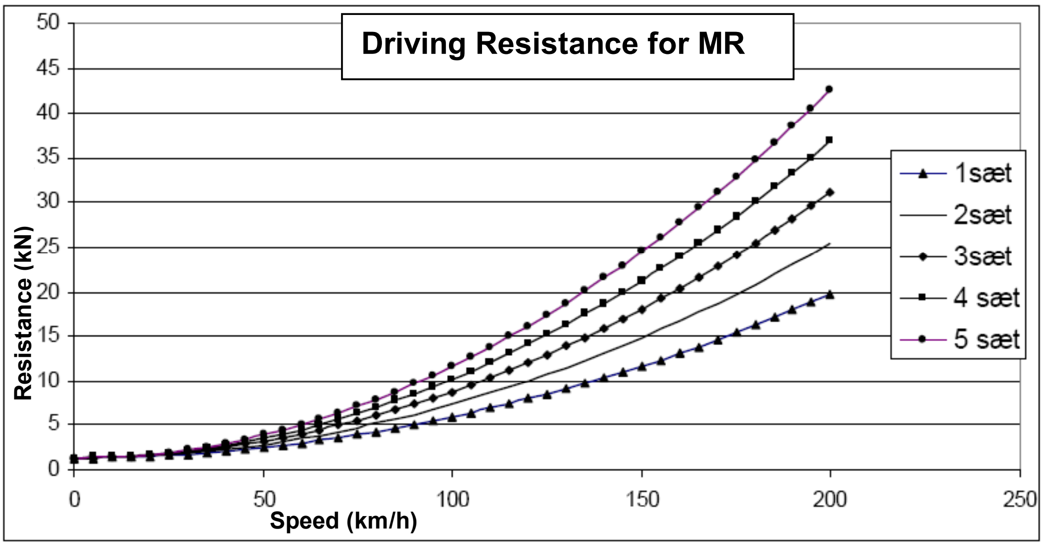


Figure 16.4. Driving resistance for up to five coupled MR sets.

17 Summary

Based on the simple analyses shown here,

- In general it is advantageous to arrange trains as homogeneously as possible, within the restriction of shunting, and loading/unloading at intermediate stops.

For flatcars:

- For wagons with side stakes, the resistance can be reduced up to between 20 and 24% by lowering the stakes.
- For wagons with containers, it is always advantageous to fill empty places with empty containers to reduce air resistance.

For open wagons:

- The resistance of open wagons can be reduced up to about 25% by covering the open hoppers of unloaded cars.

In all the above, the reduction in aerodynamic resistance will be greater than any increase in rolling resistance caused by any extra weight.

On a resistance per ton basis, a maximum variation of about ± 50% from an average value can be expected. In practice, real trains will have a lower variation.

18 Literature

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3. Gerhard Mehlhorn: Der Ingenieurbau - Fahrdynamik - Ferkehrfluβ, Ernst & Son, Berlin, 1995.

4. WS-Atkins , Private Communications, 2000.

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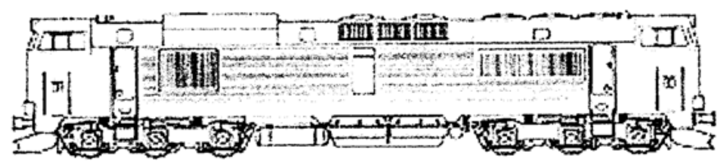
7. Roger Kaller and J.M. Allenbach, "Traction Électrique, Presse Polytechniques et Universitaires Romandes", 1995.

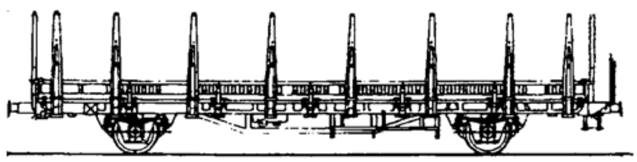
Appendix 1 Locomotive and wagons used in the calculations

Locomotive MZ4
Length: 21,0 m
Service Weight: 123 tons
Number of axles: 6
Axle load: 20,5 tons

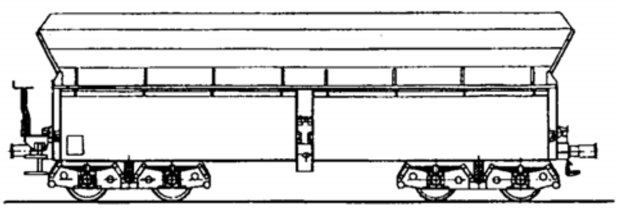


Wagon: Sgis
Length 19,64 m
Tare weight: 17,7 tons
Lax Load: 62 tons
Number of axles: 4

Wagon: Kbs
Length 13,86 m
Tare weight: 12,5 tons
Lax Load: 27,5 tons
Number of axles: 2



Wagon: Fad
Length 12,54 m
Tare weight: 25,0 tons
Lax Load: 55,0 tons
Number of axles: 4



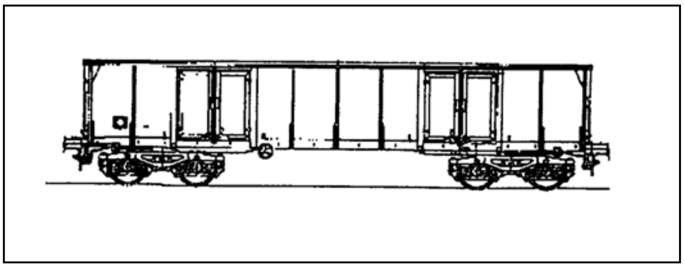
Wagon: Eaos

Length 14,04 m

Tare weight: 21,8 tons

Lax Load: 58,0 tons

Number of axles: 4



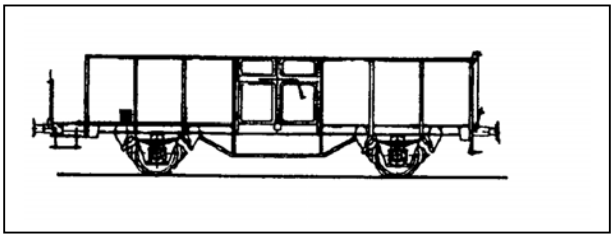
Wagon: Es

Length 10,5 m

Tare weight: 9,7 tons

Lax Load: 30,0 tons

Number of axles: 2



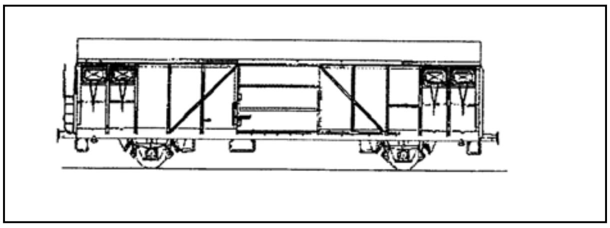
Wagon: Gls

Length 12,09 m

Tare weight: 13,5 tons

Lax Load: 36,0 tons

Number of axles: 2

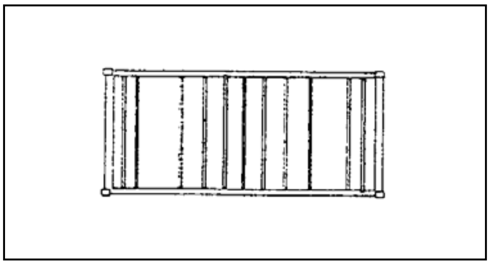


Container: DK 2210

Length 6 m

Tare Weight: 2,3 tons

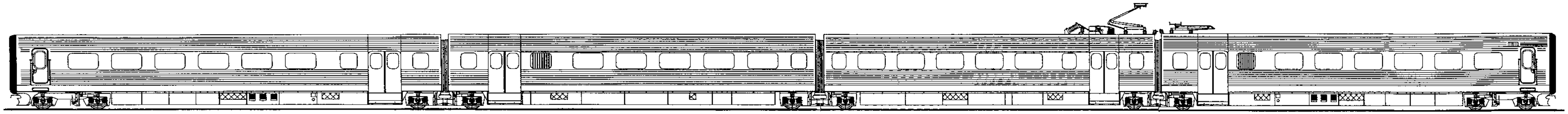
Max Load: 24,0 tons



Equipment
Source: Reference 5.

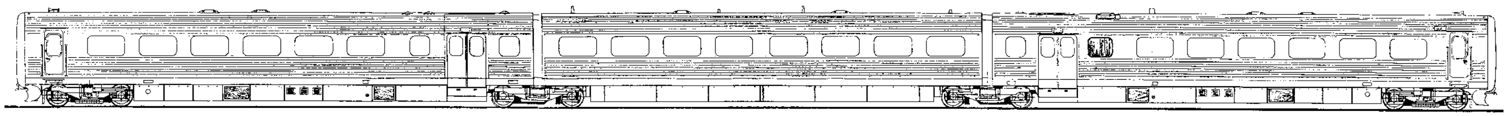
ER

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



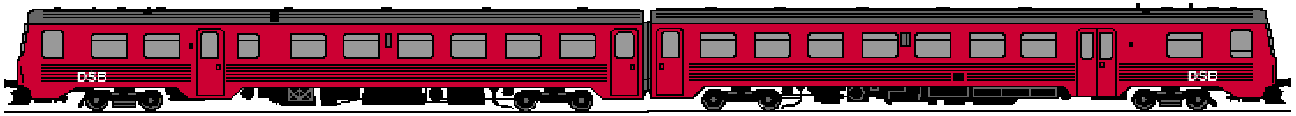
MF (IC3)

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



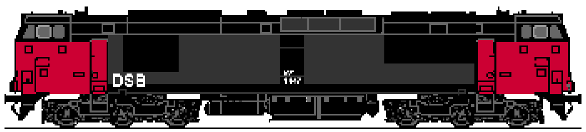
MR-MRD

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



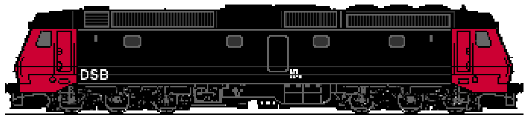
MZ4

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



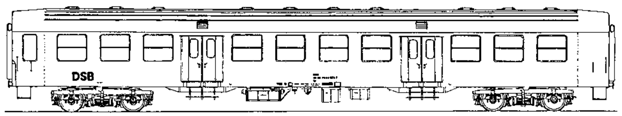
ME

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



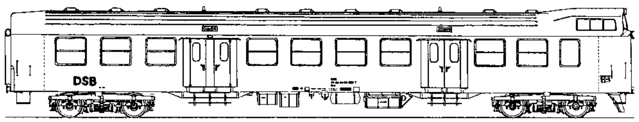
Bn

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



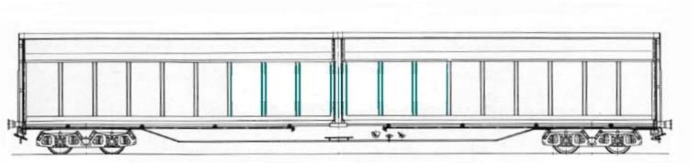
ABns

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



Habbinss-y

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



Appendix 2 Summary of areas and α-values for non-homogeneous trains.

The desired value of α is found by starting with the first wagon in the left hand column and finding the intersection with the following wagon in the second row.

	Front Area	10.86	8,07	9,97	12,22	4,7	9,77	10,84	3,45	7,32	10,85
	Following wagon	Gls	Es	Eaos	Fad	Kbs - stakes	Kbs +stakes	Kbs+ containers	Sgis - stakes	Sgis +Stakes	Sgis + containers
Rear area	First wagon										
10.86	Gls	0,00	0,00	0,00	0,13	0,00	0,00	0,00	0,00	0,00	0,00
8,07	Es	0,35	0,00	0,24	0,51	0,00	0,21	0,34	0,00	0,00	0,34
9,97	Es	0,09	0,00	0,00	0,23	0,00	0,00	0,09	0,00	0,00	0,09
12,22	Fad	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,56	0,00
4,7	Kbs - stakes	1,31	0,72	1,12	1,60	0,00	1,08	1,31	0,00	0,00	1,31
9,77	Kbs +stakes	0,11	0,00	0,01	0,25	0,00	0,00	+,11	0,00	0,00	+,11
10,84	Kbs + containers	0,00	0,00	0,00	0,13	0,00	0,00	0,00	0,00	1,12	0,00
3,45	Sgis - stakes	2,15	1,34	1,89	2,54	0,36	1,83	2,14	0,00	0,00	2,14
7,32	Sgis +Stakes	0,48	0,10	0,36	0,76	0,00	0,33	0,48	0,00	0,00	0,48
10,85	Sgis + continers	0,00	0,00	0,00	0,13	0,00	0,00	0,00	0,00	0,00	0,00

Appendix 3 Sample Calculation of the air resistance coefficient for non-homogeneous goods trains

First, consider the train consisting of kbs and Gls in for example Figure 6.1 From Table 3.3, read $c_{L,M}$ and $c_{L,f}$ for the KBS and with stakes to be 0,159 and 0.697. For Gis with closed doors, the corresponding values are 0,092 and 0,90. The length of the locomotive and cars are obtained from Appendix 1 to be 21m for the locomotive, 13,86 for the Kbs and 12,09m for the Gls.

The next consideration is that of the difference in areas between the wagons. Since the train is arranged Loco-Gls-Kbs-Gls-Kbs-Gls.......it is only half the wagons that give a positive area difference.

The area differences are obtained from Appendix 2. Choosing kbs as the first wagon and Gls as the second, the value of α is 0,11. On the other hand, if Gls is chosen as the first wagon and Kbs as the following, it is seen that α=0. It is then the Gls wagons that are highest and give the positive area difference and cause the extra air resistance. The area differences are also seen from the front/back areas, they are given at the top or the extreme left in the table in Appendix 2. All the constants are then known.

The total c_L value is determined from Equation 3.3.

$$c_{L,tot} = \sum c_{L,m} + \alpha \cdot c_{L,f} \Rightarrow$$

$$c_{L,tot} = c_{loco} + \frac{n}{2} \cdot c_{L,m-Kbs} + \frac{n}{2} \cdot c_{L,m-Gls} + \frac{n}{2} \cdot c_{L,f-Gls} \cdot \alpha \Rightarrow$$

$$c_{L,tot} = c_{loco} + \frac{n}{2}(c_{L,m-Kbs} + c_{L,m-Gls} + \cdot c_{L,f-Gls} \cdot \alpha)$$

where: $c_{L,tot}$ is the air resistance coefficient for the entire train
$c_{L,loco}$ is the locomotive air resistance coefficient
n is the total number of wagons.

Inserting values:

$$c_{L,tot} = c_{loco} + \frac{n}{2}(c_{L,m-Kbs} + c_{L,m-Gls} + \cdot c_{L,f-Gls} \cdot \alpha)$$

$$c_{L,tot} = 1{,}1 + \frac{n}{2}(0{,}159 + 0{,}092 + 0{,}9 \cdot 0{,}11)$$

$$c_{L,tot} = 1{,}1 + \frac{n}{2} \cdot 0{,}35$$

C_LA_{norm} is obtained by multiplying the value of $C_{L,tot}$ by the normal area of 10 m^2, giving: $c_{L,tot}A_{norm} = 11 + \frac{n}{2} \cdot 3{,}5$

Most locomotives or fronts of trains have similar areas with a value of the air resistance coefficient around, though somewhat lower for streamlined trains. The air resistance of the individual wagons and their combination then determines the importance of the number of wagons in the train.

The air resistance can also be expressed as a function of the length of the train. Substituting the lengths of the locomotive and the two cars, it is found that:

$$c_{L,tot}A_{norm} = 8{,}17 + L_t \cdot 0{,}0135$$