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TNO report

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On-road determination of average Dutch driving behaviour for vehicle emissions

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Summary

Context
Driving behaviour is an important factor in the determination of emission factors. As until now Dutch driving behaviour was determined based on a mix of studies, some of which are over ten years old, driving behaviour data in the Netherlands was in need of an update. Conveniently, TNO's VERSIT+ emission model is now able to accommodate hundreds of hours of data to underpin an emission factor, whereas previously VERSIT+ was only capable of processing a small set of representative driving data. Lastly, emission factors are nowadays determined based on on-road emission measurements. Driving behaviour in these measurements, as opposed to the specific real-world driving cycles that were executed in the emission laboratory in the past, is more arbitrary; it is merely dictated by the traffic situation on the road.

All in all, many good reasons exist for updating the driving behaviour underlying the Dutch emission factors. The Pollutant Release and Transfer Register project offered the opportunity to execute a measurement program enabling a general overhaul of the understanding of driving behaviour.

Approach
A test program was set up to determine driving behaviour by randomly following vehicles across the Netherlands using a high-powered passenger car with automatic transmission. The velocity signal and latitude and longitude information were recorded. An appropriate large headway distance was used, such that the actions, i.e., braking and accelerations, of the car in front were not enhanced by the car follower.

This way, all driving behaviour was determined in the same period, producing a coherent picture across the different traffic situations for the current state on the Dutch roads. The velocity data in itself was collected in a manner representative for the average driving on the Dutch roads.

Results
The project resulted in 108 hours of total driving time. In this time, a distance of 6640 km was travelled, consisting of 180 trips. The collected velocity data was linked to the different road types using the Nationaal Wegen Bestand (NWB) of 1 January 2015, yielding the following division over the road types.

Table 1 Total distance driven in this project, categorized by road type.

trip	**distance covered (km)**	**driving time (h)**	**average speed (km/h)**
urban	835	32	26
rural	1179	22	53
motorway	4625	53	87
total	**6640**	**108**	**62**

A remarkable observation was done with respect to motorway congestion. From the velocity data there are strong indications that the driving dynamics at intermediate velocities (40 km/h – 70 km/h) are larger than at low or high velocities.

At present, in the determination of emission factors, congestion is defined as all speeds under 50 km/h.
This means the highly dynamic driving behaviour at velocities between 50 and 70 k/h, and the high emissions associated with this, are not associated with congestion in the current approach but part of periods of higher dynamics during free flow driving.

The quality of the data and possible bias introduced with this method of obtaining velocity data was tested by driving with a radar. With the use of the radar also the driving behaviour of the car in front can be determined. From these tests, no significant and systematic deviations were observed. The variations were mainly the result of the delayed reaction, which offsets in velocity signals by about one second.

Conclusions
This study resulted in an up-to-date, accurate and reliable driving behaviour dataset, or ‘driving vector’. It enables an even more reliable determination of emission factors in the next years. The changes from previous studies and results are not major, but some changes are systematic. The driving dynamics are larger across all traffic conditions than previously assumed, which makes the resulting emission factors less dependent on the average velocity alone. In particular, the reduced velocity on the motorways, still above 50 km/h, increases the dynamics in motorway driving. This type of vehicle dynamics is the result of the onset of congestion, where cycles of acceleration and deceleration occur. Consequently, effects from reduced speed limits on the motorway are, for example, expected to be somewhat smaller, as part of the emissions result from dynamic driving.

Recommendation
The decision to set the boundary of motorway congestion at 50 km/h is, in hindsight, an unfortunate one for estimating emissions. The boundary is more natural at 65 km/h to 70 km/h. If the boundary is to be set at 70 km/h the increased vehicle dynamics, with an associated increase in emissions, is properly assigned to the change due to the increased congestion, and no longer as a minor fraction in the free-flow situation.

These results apply to passengers cars and vans and reflect the status quo of driving behaviour in 2015. In order to keep the data up-to-date, driving behaviour should be recorded every few year. Moreover, a similar study must be carried out for trucks as well, as there is very limited, and largely outdated information on the driving behaviour of trucks in the Netherlands.

Contents

1 Introduction

The national emissions totals for road transport and local air quality modelling rely on accurate estimates of the vehicle emissions at different locations and under different driving circumstances. The driving dynamics and, for example, the level of congestion, play an important role in the magnitude of the emissions. This requires associating generic traffic situations: i.e. road types, speed limit, and congestion to specific driving behaviour. This study establishes this relation anew for the Netherlands. The emission factors are the average emissions per vehicle and kilometre for a given traffic situation. Traffic intensity and road length will determine the total emissions.

These Dutch national emission factors are a combination of the vehicle emissions for different driving behaviour combined with the driving behaviour in different traffic situations for which the emission factors are provided. There is a main distinction in urban, rural, and motorway driving, and different levels of congestion exist for the first and latter road type. Moreover, for motorways the different speed limits and speed-limit enforcement levels are distinguished, as they have a major effect on the average emissions.

Until now, determinations of driving behaviour have been based on a mix of studies, some of which are over ten years old. In a number of cases, the study was conducted just after the introduction of the particular traffic situation, such as 80 km/h zones on the motorway with strict enforcement and the more recent 130 km/h speed limit. It is unclear if since that time some habituation has occurred and if the driving behaviour in these cases changed as a result of this habituation.

Moreover, after the adaption of the VERSIT+ emission model, this model no longer requires a small set of representative driving data, i.e., velocity profiles, to predict the emission for that traffic situation. Rather, a limit to the amount of data which can underpin an emission factor no longer exists. Hence, more data will lead to more statistics and a better prediction of the average. This also takes away an intermediate filtering, and resulting bias, of driving behaviour from a large set of driving data and a true average can be determined based on hundreds of hours of data.

Lastly, nowadays on-road emission measurements are used to determine the emission factors. In the past, specific real-world driving cycles were executed in the emission laboratory. Today, the driving behaviour in the emission tests on the road is more arbitrary; it is merely dictated by the traffic situation on the road. And what is more, ambient conditions vary on road as well. This study gives further understanding of representative driving behaviour and it will help to ensure vehicle emissions are to be tested in a representative manner for the Dutch situations.

All in all, many good reasons exist for updating the driving behaviour underlying the emission factors for road transport used for air quality modelling and for estimating national emission totals from road transport in the Dutch Pollutant Release and Transfer Register. This project offered the opportunity to execute a measurement program enabling a general overhaul of the understanding of driving behaviour.

The results of this research were submitted as Dutch input into the discussions in Brussels on representative driving behaviour forming a basis for Real Driving Emission (RDE) testing for future legislation. It is hoped this report will also serve to improve European understanding into driving behaviour and its relation to emissions.

2 Previous understanding on driving behaviour

In the past, velocity profiles were central to the determination of driving behaviour for emissions. And, despite their major shortcomings, velocity profiles are still used in many cases today. Velocity profiles originate from the need to repeat driving behaviour in the laboratory during emission tests. Using real-world on-road driving behaviour was a manner to ensure real-world emission tests in the laboratory. However, it has grown into a research effort of its own with its own jargon and methods , which, with today’s possibilities of on-road emission testing and ever deviating laboratory tests, and the use of Markov chain methods to generate driving cycles, is largely outdated.

A velocity profile is a selection of data from a large set of driving data that is somehow meant to be representative. Many researchers conclude that a short trip of twenty minutes or so is sufficient to determine the emission characteristics of a vehicle. There is limited data to support this premise. Moreover, the selection of the velocity profile, from parts of the data, is a manual process already flawed by the fact that the representative velocity profile, or the driving cycle, must be short, and it is built up of of parts of driving data, typically separated by stops. Long parts in the data, between stops, are therefore inappropriate to arrive a test with specific trip characteristics. Hence, the short parts, or subcycles, are therefore selected. Instead, a normal driver may go for half an hour or more without stops; such data is unsuited for laboratory tests.

Recently, TNO developed a random cycle generator which avoids the problem of reconstructing a driving cycle from sub cycles, and it generates second-by-second changes based on Markov chain of second-by-second driving probabilities and probabilities of transient driving, i.e., deliberate accelerations and decelerations with substantial change in average velocity.

There is a large folklore of so-called “trip characteristics”, or average trip properties, which are meant to determine the driving behaviour and the representativeness of the velocity profile for normal driving behaviour and normal vehicle use. This analysis is self-contained and it has led to erroneous, predisposed conclusions on what is normal driving behaviour. For example, based on this type of analyses, the common understanding is that driving behaviour has not changed over decades and driving behaviour does not vary with the rated power of the vehicle. An appropriate analysis tool, or the data for that matter, to investigate this in a serious manner has been lacking until now.

Another major fault with the standard velocity-profile approach is the aim at average driving. Given the fact that emissions are produced intermittently, the average driving is not a good way of determining the average emissions. The total span of driving behaviour must be weighed according to their occurrences in real-world conditions to arrive at the average emissions, as a small part of driving behaviour may result in a large part of the emissions. This may even be driving behaviour which lies outside the physical realm of the average car with a limited engine power.

These drawbacks were already understood at TNO in 2009 [Ligterink 2009] and the emission model VERSIT+ was adapted to limit their effects. TNO has been an international advocate for improving driving behaviour research. Moreover, new test cycles were developed to ensure a full span of driving behaviour as observed on the Dutch roads. In particular, the TNO Dynacycle covers the hard accelerations normally excluded in laboratory driving cycles. Since 2009, the Dynacycle has been used commonly in laboratory tests by TNO, in order to augment the emission data collection. However, this artificial cycle was only meant to compensate the lack of high-acceleration data experienced with most real-world cycles. Most standard driving cycles are designed so that low-powered vehicles can drive them, and the somewhat circular reasoning is that high-powered vehicles are driven in the same manner as low powered vehicles. The notable exception to these low-powered cycles are the De-Lijn bus cycle of the Belgian research institute VITO, with maximal acceleration to set points, and the maximal acceleration segment in the ERMES cycle.

In the past, the velocity profiles underlying the emission factors were based on one to five separate representative trips weighed together. Only recently, this restriction was abandoned, and the intermediate step via representative trips is no longer required. Current study is to make a complete adaption from so-called average, or representative, driving to the full-span of driving, to be used in the determination of emission factors.

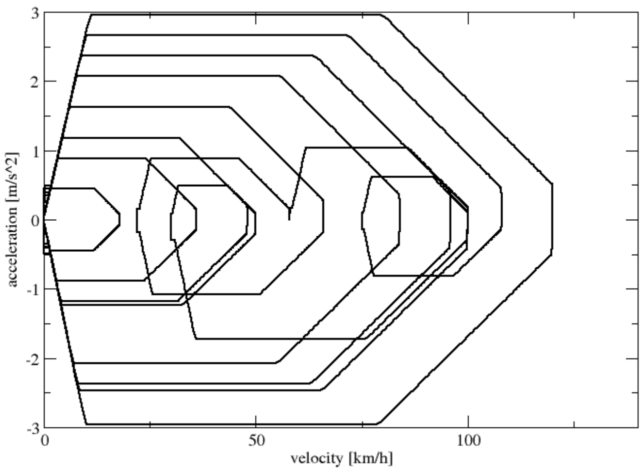

Figure 1 The TNO Dynacycle in terms of velocity and acceleration shows how in particular the hard accelerations and decelerations are covered. Some vehicle are not able to follow the hard accelerations (above 2 m/s^2), and they are instead operated at full throttle.

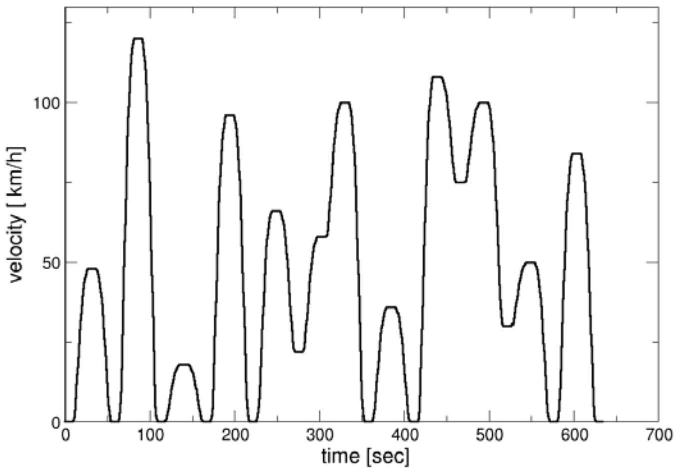

Figure 2 The TNO Dynacycle as normal velocity profile: the velocity as function of time. The variation of velocity and accelerations are dynamic. The prolonged accelerations are alternated with less demanding parts.

Driving data is collected on-road. Cars are followed in the normal traffic flow in the relevant conditions. From 2009 and earlier this data is no longer available for re-analysis, hence a detailed comparison with the findings in this report cannot be made. There are five major studies for driving behaviour from which data is currently used: [Gense 2001] [Barlow 2009] [Lange 2011]

- The ARTEMIS project has led to the Common Artemis Diving Cycle (CADC) which is commonly used across Europe to test the real-world emission performance of vehicles in the laboratory.
- The OSCAR project of TNO and TRL resulted in a number of driving cycles which are used for urban driving with different degrees of congestion.
- The Files-and-Emissies project of TNO is the main understanding of Dutch motorway driving behaviour.
- The Overschie project was carried out to determine driving behaviour in newly formed 80 km/h zones on the motorway with strict speed-limit enforcement.
- The 130 km/h motorway project was set up to study the driving behaviour on motorway stretches were the new speed limit applies.

The studies range from 2001 till 2011. Little information and data remains from the earlier studies. Typically, only the selected, or constructed “representative velocity profiles” have been carried over in time. Hence, there is little understanding of whether and how driving behaviour changes over time, due to changes in vehicle power, drivers getting used to new traffic situations, and the manner in which speed limits are enforced.

In the meantime, GPS has become ubiquitous. Several projects were carried out collecting GPS velocity data, e.g., UDRIVE. There are major flaws in this data. For starters, the quality of the velocity data is generally poor. It may look smooth and appropriate but it can in fact deviate significantly from the actual velocity, as will be shown in the current study. Moreover, the selection of vehicles, drivers, and routes is generally aimed to represent the ‘fallacious average’.

Hence, the average in many different ways will not lead to the appropriate span of driving behaviour. What is more, it will not lead to any understanding of the missing data. Again, many of such studies generate their own bias, and perpetuate the myths around so-called normal driving.

It is therefore essential to collect a large amount of random driving behaviour on the road with a good coverage of all aspects which may determine the complete span of driving behaviour for emissions and the weighing of the different data therein. Hence, a proper set-up of a test program from modern driving behaviour must be a wide as possible, without preselecting in any manner of what may be representative or average. A common fallacy is that the average driving behaviour will produce the average emissions. The aim of this project is to provide an appropriate set of Dutch driving data which spans the situations on the road.

3 Characteristics of driving behaviour for VERSIT+

In 2009, the VERSIT+ emission model had a major update [Ligterink 2009] to make the model ready for improved real-world emission measurement techniques: second-by-second data and results from on-road testing. The three essential features of the new model version are:

1. The use of a map with emission rates [g/s] for the velocity and acceleration of the vehicle as the basis for the emission model. Such a map is linear, which ensures exact post-diction and allows for averaging.
2. Dividing the map into segments relevant for road type and emission rates, such that the velocities are typical for urban (0-50 km/h), rural (50-80 km/h) and motorway (>80 km/h) driving, and a line of equal emission rates similar to a large share (~65%) of smooth driving, a smaller share (~30%) of mild accelerations and an even smaller share (~5%) of hard acceleration; all three contributing a similar amount to the total emissions.
3. A least-square regression fit of each segment of all the relevant emission data collected per vehicle category. This method ensures appropriate total emissions, as the focus is on the average emissions. The quality of the model determines to what extent each specific case is represented. Generally, for driving for which no data is collected the predictability is lower, as expected. When the predictability is low, the results default to the average emissions by design.

Essential to this approach is the collection of representative data and their full variation therein. The main principle is that the emission tests must already include the typical velocities and accelerations which are used to determine the emission factors. In that manner, the emission model is little more than a re-weighing of the emission measurement data, for variations, or selections, of velocities and accelerations.

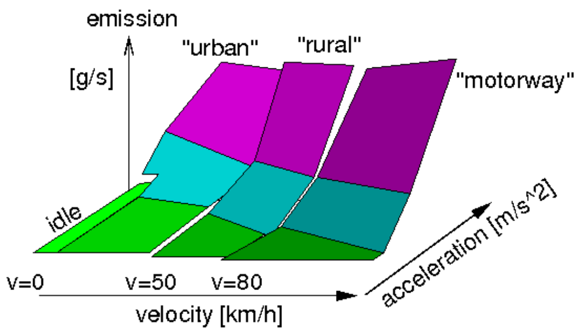

Figure 3 The emission rates are fitted as ten piecewise constant and linear parts which shapes follow the general contour lines of the emission maps. Driving behaviour is matched second-by-second with these maps to produce total emissions in VERSIT+ per emission component and vehicle category. The choice of only ten parts, or parameters, was dictated by the statistical requirements of the data as existed in 2009.

Driving behaviour, in other words, is essential to determine the actual emissions in a particular situation. A slightly smaller or larger time share of accelerations will affect the outcome significantly. In particular, the roughly 5% of the time of hard accelerations contribute typically about a third to the total emissions.

A 1% change from 5% to 4% or 6% harder accelerations will lead to a significant change in emissions of about 5% down or up.

Personal driving style can deviate a lot from the average driving style. Moreover, the power-to-mass ratio may limit the driving style with certain vehicles. Eventually, everybody drives in the same traffic flow, hence globally, or on average, there may be little differences in driving behaviour, but in the details large differences can be observed. For example, accelerating from a stop to 100 km/h on the motorway may take as short as 10 seconds for a high powered car, or as much as 60 seconds behind a heavy-loaded truck. In both cases the total $v*a_{pos}$, which is a commonly-used trip characteristic, is the same (i.e. $\sim v^2$). If this total is combined with data of constant driving to make up the total distance, the average will be the same as well. On the other hand, emissions in the first case can be twentyfold higher than in the second case, which is not compensated by the shorter period of acceleration.

4 Test program, driver instruction, and methodology

The test program of this project was set up to cover many eventualities, and to collect as much data as possible. Moreover, the data itself, i.e. without any analysis or filtering, should be representative for the span, the variation, and the average of Dutch driving behaviour.

The driving behaviour test program was carried out by randomly following vehicles across the Netherlands. The velocity was recorded in different ways, of which the calibrated wheel rotation sensor, as part of the ABS, was determined to be the most accurate. The signal was robust as well. In the many hours of driving, the signal was always available.

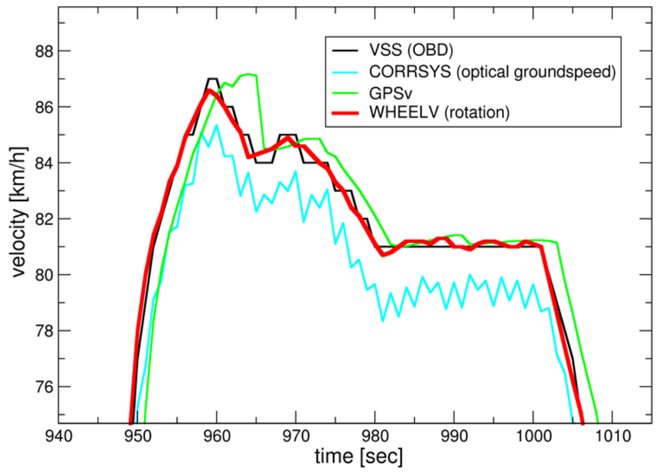

Figure 4 The different velocity signals which were recorded simultaneously. The wheel rotation sensor signal was the most accurate; the OBD velocity is somewhat stylized; the optical sensor gave a poor signal; the GPS does not follow the true velocity. The GPS signal seems to be filtered and delayed with fast corrections from time to time.

The vehicle used was high-powered with automatic transmission to allow for the following of all other vehicles in normal Dutch driving. The driver's instruction were the following:

- The driver(s) must be experienced.
- The first priority is safe and legal driving. If a car is speeding and it is safe to follow this car, it should be done for 30 seconds for the record. In the course of the project, one speeding ticket was obtained on an 80 km/h rural road with an actual speed of 90 km/h. More incidents of speeding did occur.
- The driver will use the navigation to drive from one location to the next. These are usually inner-city locations of cities that are 30-40 km apart, for a proper distribution of urban, rural, and motorway driving. On a single day, about 10 such sub-trips are driven. A greater part of the Netherlands is covered. On this route the cars in the same direction are followed.

- After every sub-trip, a five to ten minutes pause is taken, at an appropriate parking space. The equipment is left running. One or two proper breaks must be taken, to avoid drowsiness.
- The driver will follow cars in the same direction at a constant distance, so to reproduce the driving of the car in front. He, or she, will attempt to follow the passenger cars and vans with the license plate where the first number is the lowest. If a car passes, or is passed, in the lane directly adjacent with a lower number this car will be followed for as long it drives in the same direction.
- If a car is going in a different direction a nearest vehicle in front is to be followed.
- If no car is available to be followed, the driver will drive the speed limit (on the vehicle display) for that road section.
- In total about fifteen days of driving are planned. It must include the morning rush-hour, starting at 7:30).
- Two evenings of driving are included, also to monitor the driving behaviour on the motorway with different speed limits during the day and in the evening.

During the first days of testing the instructions were augmented to include the following:

- Each car is to be followed at least for a few kilometers, before a lower license plate number is selected.
- If the driver of the car in front appears to be aware that he or she is being followed, the following is to be abandoned. This phenomenon occurred a couple of times in the 15 days of driving.

To ensure that the driving behaviour was as much as possible representative of the cars followed, the driving behaviour was evaluated during driving on the first day together with the author of this report:

- An appropriate large headway distance was used, such that the actions, i.e., braking and accelerations, of the car in front were not enhanced by the car follower, in order to maintain constant headway.
- Following the slow right-lane vehicles, which fulfilled the selection criteria, were to be included better. Cars stuck behind trucks on the motorway are easily ignored due to the lack of space and time to merge behind smoothly.

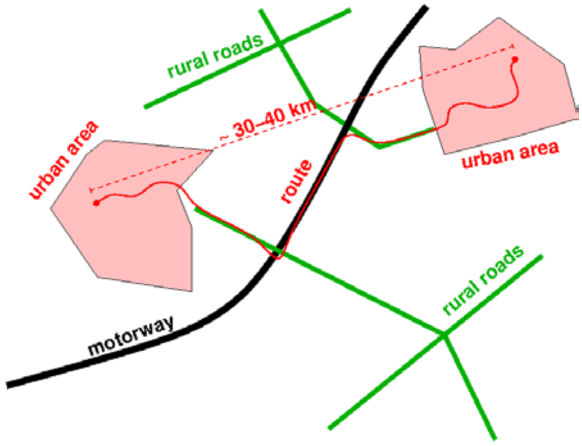

Figure 5 A typical trip, depicted in red, which includes urban, rural, and motorway driving in more or less the Dutch ratio. The start and stop are usually at shopping centres in residential areas away from the motorway access. The typical trip distance is approximately 50 km.

The experiences of the driver were the following:

- In urban driving there is very little choice but to follow the car in front. This means in urban trips usually only a few cars are followed.
- On the motorway, some cars accelerate quite aggressively, in particular if a slower vehicle is blocking the fast lane for some time. As the slower vehicle vacates the fast lane, some tailing cars speed off.
- The 130 km/h sections on the motorway are often short and/or the 130 km/h stretch is poorly indicated. As a result, many cars remain driving at a slower velocity. Only in the northern provinces the long stretches of daytime 130 km/h speed-limit motorways seem to have led to a substantial velocity increase over 120 km/h speed limit.

The project resulted in 108 hours of total driving time. In this time, a distance of 6640 km was travelled, consisting of 180 trips. Of this time, twelve days consisted of typically 11 ordinary trips per day. To increase the share of rural driving the motorway was avoided on one testing day (18th of September 2015). As it turns out, in many cases the normal navigation generates a preference of motorways over rural roads. The testing period started at the end of the last school summer holiday period on 31 August 2015 and ended on 21 September 2015. It included two weekday evenings, a Saturday, and a Sunday. On some days a substantial amount of motorway congestion was observed, typically associated with traffic incidents.

Figure 6 The project resulted in 108 hours of total driving time. In this time, a distance of 6640 km was travelled, consisting of 180 trips. The map shows the total route in red.

The collected data consists of velocity signal and latitude and longitude information. During the trip, a front-view camera was recording data to check particular incidents in the velocity data. In practice, the camera recording did not add much to the current study. The velocity data was accurate and did not contain unexpected, or improbable, results.

Figure 7 A video frame from the data, showing the typical headway distance the driver kept in motorway driving.

The velocity data is very rich and diverse. For example, as Figure 8 shows, congestion on the motorway does not have a natural pattern which uniquely identifies congestion, but varies smoothly from free flow towards stop and go. However, notably is the oscillatory behaviour of variations of 40 km/h while entering and leaving a region of heavy congestion on the motorway.

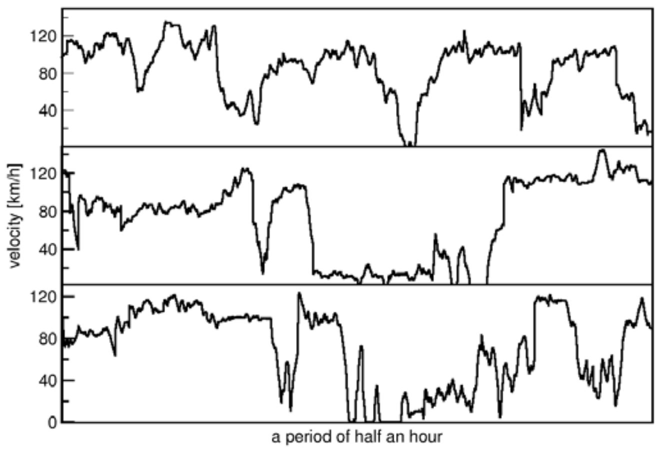

Figure 8 Three arbitrary selections of motorway driving in the case of reduced velocity. The dynamics seems especially large around 50 km/h.

5 Separation into road types and congestion levels

The collected velocity data was linked to the different road types using the Nationaal Wegen Bestand (NWB) of 1 January 2015. This data contains all road segments in the Netherlands per maintainer. The maintainers: “rijk”, “provincie”, and “gemeente” have been used as proxy for the generic definitions of motorway, rural, and urban. Since the GPS data has limited accuracy, the map of the Netherlands is divided into 0.0025° x 0.0025° squares.

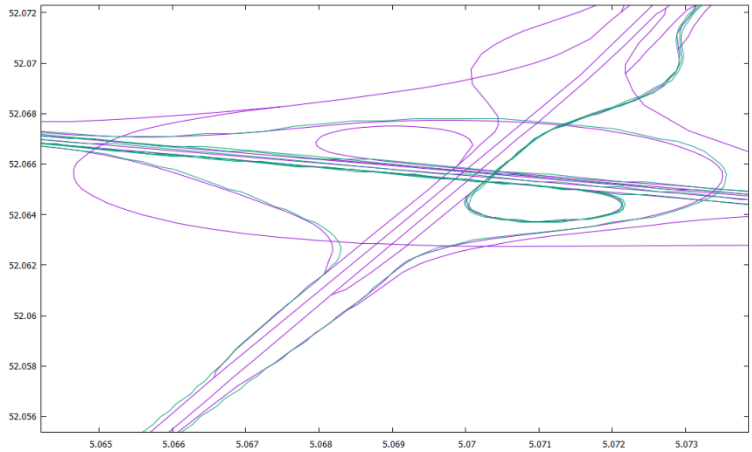

Figure 9 The motorway junction Ouderijn in the NWB data in magenta and the velocity data overlaid in green. In the 15 days of driving, the car has passed this junction several times as part of the different routes. The axes are decimal degrees longitude and latitude.

In the case a motorway was present in a square, the driving was assigned to motorway, if a provincial road was present the road type was designated rural, and otherwise a urban road was assumed. Periods of limited accuracy and signal loss, for example caused by driving through tunnels, sometimes occurred on motorways and rural roads. In such a case, the last-registered road type was retained for a period of 50 seconds.

Table 2 Total distance driven in this project, categorized by road type.

trip	**distance covered (km)**	**driving time (h)**	**average speed (km/h)**
urban	835	32	26
rural	1179	22	53
motorway	4625	53	87
total	**6640**	**108**	**62**

Table 2 shows the road type breakdown of the total test trip. The high fraction of motorway seems natural for Dutch driving. However, the data is slightly biased by a number of special motorway trips in the evening to cover the evening driving styles, resulting from different speed limits.

5.1 Time dependence

The driving was executed during the whole day, including at least one rush hour, but in many cases both the morning and the evening congestion was included. Nowadays the traffic intensity in the Netherlands varies only limitedly throughout the day from 7:00-18:30, and only a few percent more traffic in the rush hour periods is enough to tip the balance and generate congestion. Hence, the program is more or less representative for the total distance travelled. In order to estimate the effect of the morning rush hour on the average velocity, the data is grouped into start times before 9:00, the period 9:00-16:00, and after 16:00. A full trip is used to avoid bias from a long congestion period spilling over after the normal rush hour. The trips that start before 9:00 have an average velocity of 70.8 km/h +/- 12.6 km/h. The 9:00-16:00 trips have an average velocity of 72.1 km/h +/- 11.5 km/h. After 16.00 the average is 65.8 km/h +/- 22.1 km/h. The evening rush-hour seems to have some heavy congestion periods, typically caused by incidents, yielding a lower average velocity and larger variation, unlike the morning rush hour which yields a similar velocity distribution as the rest of the day.

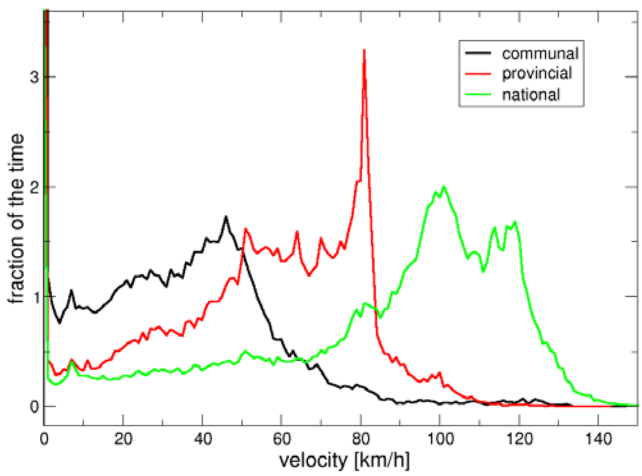

Figure 10 The distribution of velocities for the main road types. Road types were deduced from the national map data (NWB). Speed limits show up as spikes. Above 120 km/h the picture is more diffuse because drivers do not always try to maintain the speed limit as their driving velocity.

5.2 Motorway driving

5.2.1 Speed limits on Dutch motorways

In the case of motorways the different speed limits were deduced from the information published by the Dutch road authority (Rijkswaterstaat, September 2015). The colour maps for daytime and evening speed limits were used to match the velocity data to the different speed limits on the motorway. This data does not include the dynamic speed limits, associated with an additional congestion lane (“spitsstrook”). This kind of information is not used in separate the emission factors. The main speed limit is used for the road segment, not the dynamic speed limit. Hence the lower, yet constant, velocity observed in the case of 120 km/h and 130 km/h are probably associated with the reduced speed limit.

The data contains therefore probably significant fractions of reduced speed limits. If the usage of emission factors is adapted to separately incorporate lower speed limits, e.g., in the care of a “spitsstrook”, this will require an update of the driving behaviour. The frequency of occurrences is hopefully well-represented by the collected velocity data.

Figure 11 The daytime (6:00-19:00) velocity limits on the motorway as published by the Dutch road authority for the period during which the current study was executed (green: 130 km/h, orange: 120 km/h, red: 100 km/h, and purple: 80 km/h).

Figure 12 The evening (19.00-6.00) velocity limits on the motorway (green: 130 km/h, orange: 120 km/h, red: 100 km/h, and purple: 80 km/h).

5.2.2 Assigning motorway data to speed limit categories

The data assigned to motorways is further split into the different speed limits on the basis of these maps. However, the maps are not very accurate. Therefore 2 x 2 km blocks are used to assign velocity data to the appropriate speed limits.

This poses a minor problem for the identification of the limited number of road sections of 80 km/h, which are typically short. An overlap of 2 km will already lead to a significant misrepresentation. The velocity data was in this specific case filtered further.
The emission factors are generated for different situations on the motorway. The following velocity data is underlying the different categories:

- Motorway average: all motorway data (used for determining national emission totals).
- Motorway congestion: all motorway data below 50 km/h.
- Motorway 80 km/h with strict enforcement: motorway data at 80 km/h speed limit locations, truncated at 80 km/h and standard above 50 km/h for all free flow situations.
- Motorway 80 km/h without strict enforcement: motorway data at 80 km/h speed limit locations truncated at 90 km/h (to exclude crossover data to higher speed limits).
- Motorway 100 km/h with strict enforcement: motorway data at 100 km/h speed limit locations truncated at 100 km/h.
- Motorway 100 km/h without strict enforcement: all motorway data at 100 km/h speed limit locations.
- Motorway 120 km/h: all motorway data at 120 km/h speed limit locations.
- Motorway 130 km/h: all motorway data at 130 km/h speed limit locations.

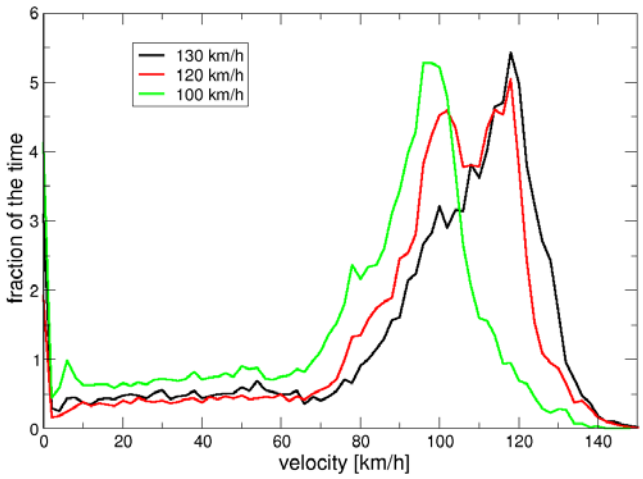

Figure 13 The distribution of velocities for the three main motorway velocity limits. The second peak at 100 km/h at the 120 km/h speed limit may be partly due to congestion lanes ‘spitsstroken’ (additional lanes that are made available during rush hour), with a reduced dynamic speed limit.

It should be noted that the velocity distribution obtained in this study is slightly higher: a few km/h than observed in averaged, and localized, data from different motorway induction loops. The amount of low velocity data is representative for the amount of congestion observed in 2015, prior to the last quarter.

The definition of strict enforcement and the implementation thereof in the driving behaviour has been a matter of some debate in the Netherlands. The enforcement by camera's to register the time travelled over a longer distance is usually assumed. There is no data available of the road segments where such enforcement was present during the study period. Instead, the data was separated into all velocity data for a given speed limit as the normal situation. A subset of velocity data with only data below the actual speed limit is used as the velocity data in the case of strict enforcement of the speed limits.

5.2.3 *Motorway congestion*

From the velocity data there are strong indications that the driving dynamics at intermediate velocities (40 km/h – 70 km/h) are larger than at low or high velocities (Figure 14). At the onset or end of heavy congestion, with an average velocity below 20 km/h, drivers seem too eager to maintain a high(er) desired velocity, which leads to velocity oscillations in the traffic flow, with high dynamics and, consequently, high emissions as a result. At the moment, in the determination of emission factors, congestion is defined as all speeds under 50 km/h. This means the highly dynamic driving behaviour at velocities between 50 and 70 k/h, and the high emissions associated with this, go unnoticed in the current approach, and is part of the dynamics underlying the emission factors in the free-flow situations.

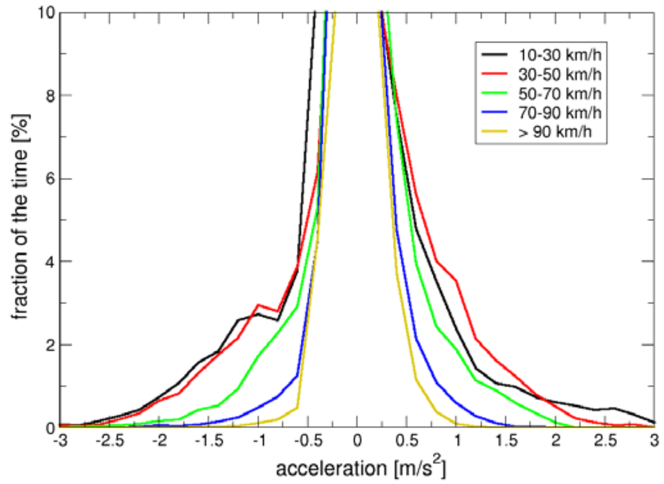

Figure 14 The distribution of accelerations in different velocity ranges on the motorway. Notably, the 30-50 km/h range has more accelerations of 1 m/s^2.

In normal driving, the magnitude of acceleration decreases with increasing velocity. Not so on the motorway: the high accelerations (> 1.m/s^2) occur the most at velocities in between 30-50 km/h.

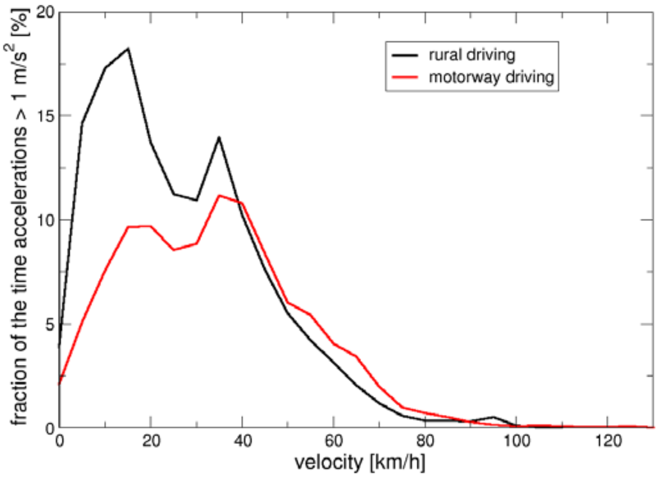

Figure 15 The fraction of accelerations above 1 m/s^2 decreases with velocity for rural driving, while a maximum occurs at 40 km/h for motorway driving. The actual magnitude of the fraction is determined by the amount of deliberate accelerations over the amount constant driving. Rural driving has more stops and therefore a higher fraction of deliberate accelerations, above 1 m/s^2, but from a stop the high accelerations occurs mainly at lower velocity.

The maximum acceleration of the vehicle depends strongly on the velocity. Given an average car of 75 kW and a weight of 1300 kg, the maximum acceleration, ignoring gear ratios and driving resistance is:

$$a_{max}\ [m/s^2] < 200/v\ [km/h]$$

Hence, as the velocity increases the physical limitations for hard accelerations are large. Given the increase in air-drag and the rolling resistance with velocity, this limitation is an over-estimation.

Generally, it is therefore expected that the magnitude of acceleration decreases with velocity. The fact that most hard accelerations occur at 40 km/h on the motorway is due to the specific driving dynamics related to traffic intensities close to the critical intensity. These types of oscillations are well-known phenomena in the study of phase transitions and critical, i.e., unstable processes. Hence, the decision to set the boundary of motorway congestion at 50 km/h is, with hindsight, an unfortunate one for estimating emissions. The boundary is more natural at 65 km/h to 70 km/h. In the latter case the increased vehicle dynamics, with an associated increase in emissions, is properly assigned to the change due to the increased congestion.

5.3 Rural driving

The rural driving data is associated with provincial roads where on the through roads the typical speed limit is 80 km/h, but occasionally 60 km/h and 100 km/h are the maximum speed.

This definition is based on the road maintainer and it usually transcends the local roads and the different city limits. The 80 km/h speed limit shows up very neatly as an isolated peak in the velocity data, as Figure 10 showed earlier.

Contrary to general understanding, the stops and the low velocity is limited on rural roads. Only in the case of agricultural mobile machinery situations of low velocity and even stop-and-go traffic occur. Clearly, in many cases these roads do not reach their maximum capacity, and free-flow conditions are common. Very likely the bottlenecks for the intensity lie at the urban or the motorway end of the rural road. It is also possible that the capacity is not tuned across the network, and a few bottlenecks ensure a limited intensity in general and free-flow conditions on the remainder of the network. On motorways, on the other hand, with the removal of successive bottlenecks the whole network is, more or less, critical for congestion and reduced velocity.

5.4 Urban driving

The emission factors for urban roads are for congestion, normal, and free-flow driving. In order to make this distinction according to the official definitions in the air quality assessment of average velocity and number of stops, the average velocity over a kilometre was determined in the urban velocity data. The instantaneous velocity data would lead to a strange bias where stops are associated with congestion only. The distance of 500 metres behind and 500 metres ahead are included in this determination of the average velocity. Driving behaviour associated with congestion may not necessarily be associated with a high urban traffic intensity (i.e., stop-and-go traffic), but a low average velocity can also be the result of traffic lights, narrow streets, sharp bends, consecutive junctions, speed bumps, or 30 km/h zones.

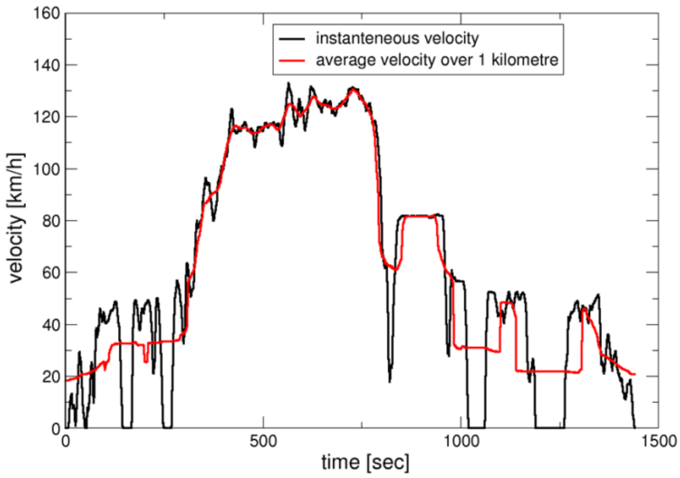

Figure 16 The instantaneous velocity and the resulting average velocity by averaging over one kilometre (500 metre before and 500 metre after). Despite the stops, the average velocity is associated mainly with normal and free flow driving.

The three congestion classes for emissions (congestion, normal and free flow) are based on representative situations. These situations are assumed to be the middle of the band in which all the driving behaviour lies. Therefore the velocity data is binned according to the average velocity below 20 km/h and above 30 km/h. Normal urban driving is at an average velocity in between 20 km/h and 30 km/h. This definition deviates slightly from the official definition in the air quality assessment of velocities below 15 km/h. The average velocity at a location is slightly lower than the average velocity over a kilometre, as the parts with the highest velocity usually dominate the latter. Therefore, in light of the different average velocity determination, instead of a lower limit of 15 km/h for normal driving a limit of 20 km/h is used.

Prior to this velocity data collection, the “average urban driving”, as used in the Pollutant Release and Transfer Register (PRTR), was assumed to be identical to the “normal urban driving”, as used in the ‘Standaard RekenMethode I’ (SRM I) for air quality modelling. Given the representative collection of velocity data, a distinction between average and normal is now possible. The sum of congested, normal, and free-flow driving can be weighed to an average based on the frequency of occurrences in normal trips throughout the Netherlands including both large and smaller cities. In the current study, 18% congested, 25% normal, and 57% free-flow urban distance at average velocities of 12 km/h, 25 km/h, and 44 km/h respectively are found. Consequently, the average driving that is used for the PRTR leads to a slightly higher average velocity and lower dynamics than normal driving used for SRM I, due to the relatively large share of free-flow driving at relatively high velocity.

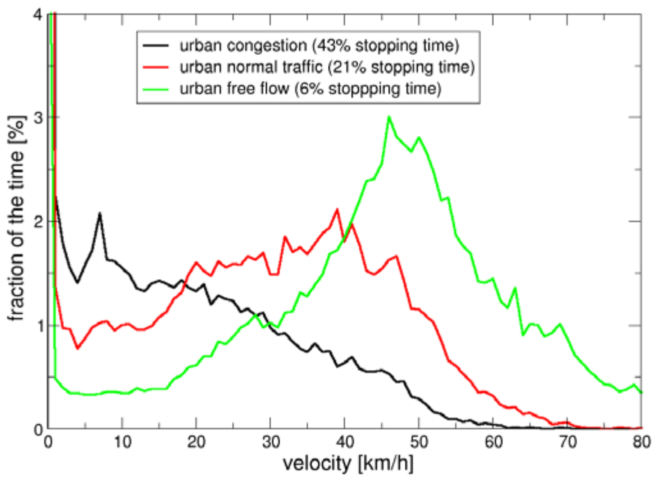

Figure 17 The velocity distribution of urban driving (‘gemeentelijke wegen’) in the three urban classes. The fraction of stopping time (v < 1 km/h) is off the scale and they are indicated in the legend.

A substantial part of urban free-flow driving is above the typical Dutch urban speed limit of 50 km/h. In part this may be the result of speeding, but in part this also is the result of higher speed limits on the main access roads into different cities.

6 Results and consequences for emission factors

6.1 Driving vectors

The driving behaviour serves as input for the emission model VERSIT+, and can be be characterized in simple tables. These tables are the fractions of time of driving at different velocities and accelerations normalized to 1 kilometre of total distance travelled. The different fields represent: [Ligterink 2009]

1. Idling time
2. Time of velocities between 0-50 km/h
3. Normalized time of mild acceleration between 0-50 km/h
4. Normalized time of hard acceleration between 0-50 km/h
5. Time of velocities between 50-80 km/h
6. Normalized time of mild acceleration between 50-80 km/h
7. Normalized time of hard acceleration between 50-80 km/h
8. Time of velocities above 80 km/h
9. Normalized time of mild acceleration above 80 km/h
10. Normalized time of hard acceleration above 80 km/h

The normalized time refers to the sum magnitude of acceleration and velocity ($a[m/s^2] + v$ [km/h]/70) above a limit value. Given the fact that the emission map is linear, the sum emission arises in the same manner from a few high accelerations or more low accelerations. The normalized value represents the appropriate sum. The ten parameters above, which characterize driving behaviour, are referred to as the driving vector (q1, q_2, q_3, …, q_9, q_{10}). In some cases a q_0 is added, which represents the fraction of cold starts per kilometre. Given these result, automatically a number of average properties can be reconstructed:

- Total idling time [s] per kilometre is q_1.
- Percentage of idling time is $q_1/(q_1+q_2+q_5+q_8)$.
- Average velocity is $v[km/h] = 3600/(q_1+q_2+q_5+q_8)$.
- Fraction of time of congestion on the motorway: $(q_1+q_2)/(q_1+q_2+q_5+q_8)$.

In other words, many interpretations and general properties can be directly derived from these driving vectors q.

The driving behaviour vectors allow for different emissions to occur in the case of hard accelerations in urban, rural, and motorway driving. Generally, the emissions do vary in the three cases, as, for example, accelerations in urban situations are usually hard and short, while on the motorway, due to the limited power available, accelerations are lower and more prolonged. The emission measurements determine the actual effect of hard accelerations in the different cases.

6.2 Emission factors

Emission factors in g/km are a simple vector product of the emission map u and the driving vector q:

$$EF[g/km] = q_1*u_1 + q_2*u_2 + q_3*u_3 + \ldots + q_8*u_8 + q_9*u_9 + q_{10}*u_{10}$$

This already dictates the approach towards the determination of both the driving behaviour and the emission maps. Hence the determination of the emission map u from the emission data is central to generating the appropriate input for the model. It should be noted that certain laboratory driving cycles do not contain data for example for hard acceleration in rural or motorway, i.e., $q_7 = 0$ or $q_{10} = 0$. This means such emission tests are insufficient or inappropriate to generate emission factors for normal Dutch driving. Moreover, given the actual small driving behaviour vector components $q_i \sim 1$ or less underlying the Dutch emission factors representing only a few percent of data, it is clear that a sufficient amount of data must be collected in order to have enough statistics for a reliable value for in particular u_7 and u_{10}. Even with a few percent of the time of hard accelerations, the magnitudes of u_7 and u_{10} are high enough for the product of a small q_7 and q_{10} with large u_7 and u_{10} to account for 20% or more of the total emissions in specific cases.

Table 3 The average driving behaviour vectors for the three main road types.

q	**urban**	**rural**	**motorway**
q_1	39.93	6.93	1.47
q_2	76.37	19.57	5.07
q_3	44.39	12.27	2.81
q_4	8.56	2.92	0.58
q_5	21.28	30.28	5.71
q_6	18.63	28.37	5.51
q_7	2.32	3.61	0.88
q_8	1.38	11.34	29.05
q_9	1.03	8.37	28.61
q_{10}	0.07	0.33	3.39

The average driving behaviour in Table 3 arises from a split of all the data to the different road maintainers: national, regional, or local. The urban driving in Table 4 is differentiated further by distinguishing the one-kilometre average velocity.

Table 4 The driving behaviour vectors for urban driving based on the average velocities.

q	**urban congestion**	**urban normal**	**urban free flow**	**urban average**
q_1	147.95	36.10	6.21	39.93
q_2	148.29	97.46	43.54	76.37
q_3	73.64	57.88	28.89	44.39
q_4	12.67	11.22	6.05	8.56
q_5	4.51	13.01	30.41	21.28
q_6	3.84	11.13	26.77	18.63
q_7	0.49	1.50	3.28	2.32
q_8	0.00	0.06	2.41	1.38
q_9	0.00	0.04	1.80	1.03
q_{10}	0.00	0.00	0.12	0.07

The average is not a simple weighed sum of the three congestion classes. The low velocity contributes a larger amount to the time than to the total distance.

These q vectors represent the time associated with one kilometre, and require a conversion from the total time: q[s/km] = samples/distance. For each q vector, the distance is to be determined together with the number of seconds per congestion class.

For the motorway in Table 5, the split of all the motorway data is made in a similar manner. However, congestion, defined as velocity below 50 km/h, is to be separated from the normal free-flow situation. The simplest solution is to set $q_1 \ldots q_4$ to zero, i.e., to time driven at velocities below 50 km/h. However, this is not natural, as some minor low velocity is to be expected also in the free flow situation. The lowest fraction of driving behaviour below 50 km/h is selected for all free-flow motorway traffic. This is 3 seconds per kilometre and it is for example associated with acceleration or deceleration on ramps.

Table 5 The driving behaviour vectors for the different speed limits on the motorway. MSH is "met strenge handhaving", i.e. with strict speed-limit enforcement, and ZSH indicates the traffic situation without such enforcement.

q	congestion	80 km/h MSH	80 km/h ZSH	100 km/h MSH	100 km/h ZSH	120 km/h	130 km/h
q_1	36.49	0.00	0.00	0.00	0.00	0.00	0.00
q_2	125.55	3.31	3.31	3.31	3.31	3.31	3.31
q_3	69.53	1.88	1.88	1.88	1.88	1.88	1.88
q_4	14.23	0.40	0.40	0.40	0.40	0.40	0.40
q_5	0.00	31.83	18.71	9.89	7.59	3.33	3.07
q_6	0.00	31.38	18.45	9.62	7.39	3.28	2.98
q_7	0.00	4.21	2.48	1.51	1.16	0.60	0.59
q_8	0.00	9.39	21.48	28.17	28.98	30.58	29.58
q_9	0.00	6.22	16.59	23.28	26.02	30.74	31.37
q_{10}	0.00	0.21	0.83	1.08	2.05	3.82	4.73

The hard accelerations between 50-80 km/h represented by q_7 as observed in the examples of transient driving on the motorway in Figure 8 are still limited in the driving behaviour vectors. In general, driving on the motorway is quite constant, reducing the fractions of high dynamics. However, part of the result arises from a bias by selecting the limit of 50 km/h for congestion. The hard accelerations in motorway congestion below 50 km/h are substantial, and a hard truncation at 50 km/h may remove additional effects for the typical waves of accelerations and braking observed in the onset and end of heavy congestion.

6.3 Particular emission events

The emission rate maps u, to be combined with the driving behaviour vectors q, may vary greatly from vehicle technology to vehicle technology. However, the VERSIT+ model is designed to be well conditioned, which means that for average driving each product $q_i * u_i$ has a similar contribution to the total emissions. From that it is clear that the ratio of u_2 or u_3 to u_4 may be a factor ten or more, similarly for u_5/u_6 to u_7 and u_8/u_9 to u_{10}. This means the emission rate at hard acceleration is ten times higher, or more, than a moderate driving. In part this is due to the additional power demand, as CO_2 emission maps exhibit similar behaviour, albeit less severe.

In many cases, the ratio of emissions (e.g. NO_x/CO_2) increases with the magnitude of acceleration. Recently, it is becoming increasingly clear that also short and slow dynamics affects this ratio of NO_x/CO_2. For example, a longer duration of acceleration will lower the NO_x/CO_2 emission rates ratio.

7 Uncertainty and bias analyses with radar data

The car-following method is a method to collect quickly a representative sample of driving behaviour on roads and routes of interest. The question remains what the accuracy and representativeness of the collected data is. This, of course, depends very much on the capabilities and instruction of the driver in the instrumented car. In a later stage of the project a radar was instrumented in a car to not only collect the data of the instrumented car, but also the velocity and acceleration data from the car in front.

The radar determines the distances and relative velocities of multiple targets. The radar also detects stationary objects, and objects further away. If the stationary radar targets are removed and the closest target from the remainder is selected a majority of the radar data has a target identified as a car in front.

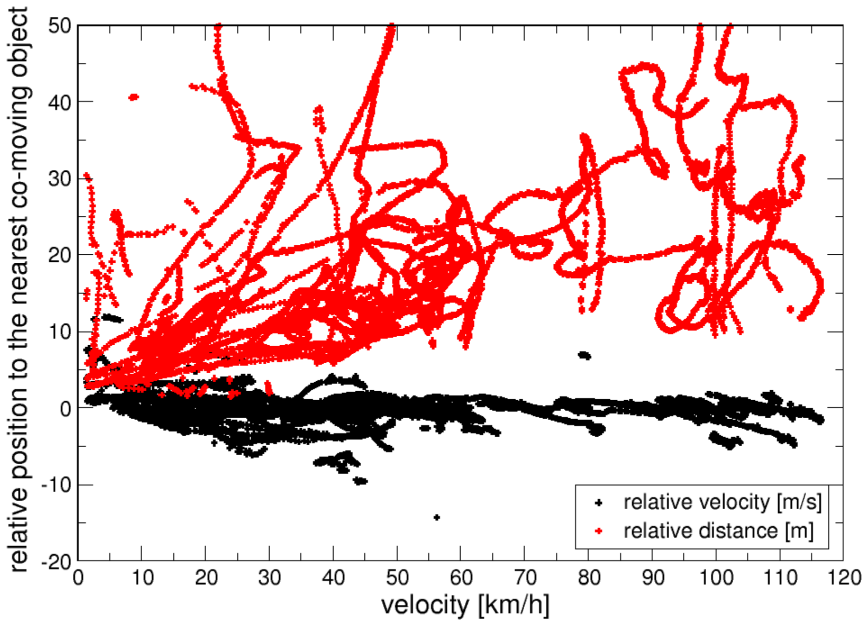

Figure 18 The radar data from a trip of 1800 seconds, with the relative velocity [m/s] in black, and the relative distance [m] in red. For 64% of the time a co-moving object is identified.

The typical following distance seems large for the Netherlands. The shortest distances in Figure 18 for the different velocities is still enough to avoid safety issues and enhanced reactions. In the case of short distances, the driving behaviour of the chase car may enhance the transients of the car in front. With the current distances this does not seem to be the case.
From the radar data it seems more appropriate to use the combination of vehicle velocity of the instrumented car and radar distance to determine the driving behaviour of the cars in front, with respect to the instrumented car, than to use relative velocity or relative acceleration.

The reason is very simple: there is no instantaneous relation between the two vehicles, but a delayed reaction dependent of the velocity and inter-vehicle distance. In the case of a perfect car-chase: 3 seconds delay with the car in front, with a slow change to the ideal car distance of 15 metres and the additional distance associated with one second delay. The simulation shows a natural variation in the inter-vehicle distance, even if the driving behaviour is perfectly replicated with a delay.

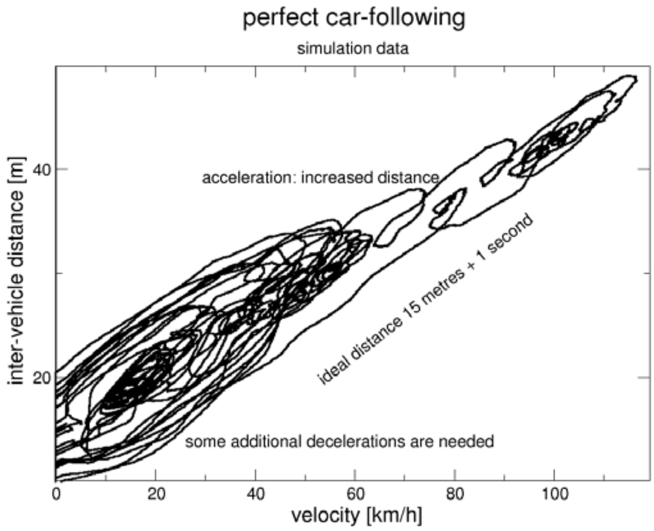

Figure 19 The perfect car following, with a constant time delay is possible, except for a few cases of hard decelerations, where additional braking of the car-follower may seem required. In the case of acceleration the distance increases due to the delayed reaction, while the distance decreases in the case of braking. A soft driving behaviour is included to retain the ideal distance.

Even in an ideal case the variation of the inter-vehicle distance is 10-15 metres. The variation observed in the radar data therefore seems only natural. Hence it is not expected, due to the delay of the car-follower, that the velocity difference is always zero. However, the velocity difference is centred tightly around zero.

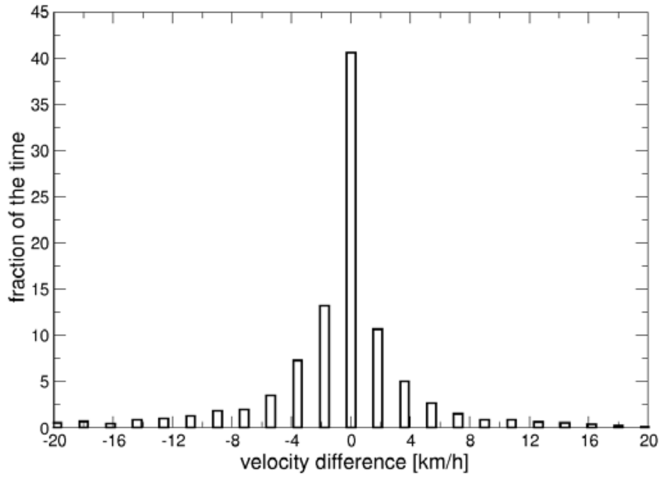

Figure 20 The time shares of velocity differences with the car in front from the radar data. More than 40% of the time the velocity difference is smaller than +/- 0.5 m/s, despite the delayed reactions in the case of car following.

If a delay, or reaction time, is assumed, the velocity differences of the car in front and the following car is even smaller than based on the radar-based velocity difference alone. In that case almost 50% of the time the velocity difference is in between the -0.5 m/s to 0.5 m/s, compared to 41% for the raw radar signal for the relative velocity. The comparison of accelerations is less straightforward as the numerical differences of the radar and vehicle velocity signals are somewhat noisy, which affects the quality of the comparison of accelerations. The symmetric distribution of the velocity differences indicates there is limited bias. If the car accelerates harder to catch up than decelerates to keeps its distance, the positive velocity difference would be larger than the negative velocity difference. In Figure 21 an example of the velocity of the instrumented car and the reconstructed velocity of the car in front is determined. Globally, the delay in velocity of the instrumented car is about one second: At acceleration the velocity is lower than the car in front and at deceleration the velocity is higher than the car in front. In both instances, one second later the velocity the same. Focussing on the details, the chase car occasionally accelerates harder, and in other cases less hard, compared to the car in front. The velocity is not completely identical, but shows no artefacts such as hard accelerations to catch up, or hard deceleration to avoid collisions.

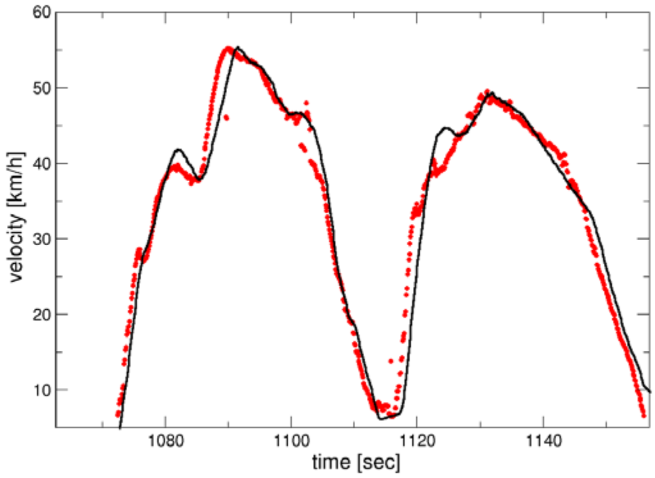

Figure 21 A sample of typical data of the chase car in black and the radar data in red. Occasional signal loss in the 10 Hz radar data can be observed, and the car in front reacting about one second ahead of the chase car. Gear shifting in the car in front is clearly visible (the instrumented car was equipped with a CVT transmission).

From these preliminary analyses it is clear radar data can assist to check the accuracy of the car following. In about 45% of the time the velocity difference is less then 0.5 m/s. Moreover, the correlation between the acceleration of the instrumented car and the velocity difference with the car in front is:

$$v_{difference}[m/s] \sim 0.84 * a_{chase}\ [m/s^2]$$

which corresponds with a delayed reaction of 0.84 seconds in both the case of acceleration and of deceleration. The systematic deviation occurs in transients where the instrumented car reaches the same velocity about 0.84 seconds later. Such delay is common for human reaction times. Velocity differences occur mainly at low acceleration. Hence they are not related to increased dynamics for transient driving. The data shows little hints of deviating dynamics apart from the delayed reaction. Therefore it is concluded that some deviation exists between the driving behaviour of the car in front and the chase car. However, these differences are small. Moreover, there are no indications that a systematic bias is introduced with this method, and with this driver, of obtaining representative driving behaviour on the road.

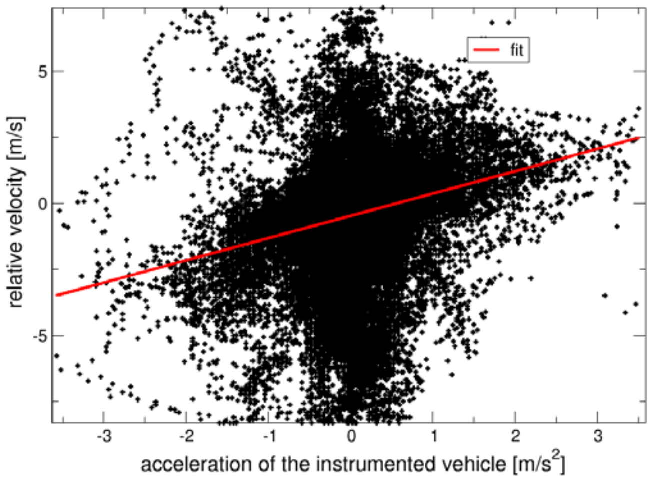

Figure 22 The scatterplot of all the car-following radar data, showing transient driving (accelerations and decelerations) naturally related to the velocity differences. The fit is the reaction time. The reaction times of 0.84 seconds seems slightly lower with decelerations than with accelerations.

8 Discussion and conclusions

For the first time the driving behaviour recorded on the road is directly translated to the driving behaviour underlying the emission factors, without restriction, selection, or filtering. Moreover, all driving behaviour is determined in the same period, and can be characterised as the state of affairs in 2015, producing a coherent picture across the different traffic situations for the current state on the Dutch roads. The velocity data in itself is collected in a manner representative for the average driving on the Dutch roads. Velocity data is collected from the wheel rotation sensor, which is much more accurate and reliable than GPS velocity.

The changes from previous studies and results are not major, but some changes are systematic. The dynamics is larger across all traffic conditions than previously assumed, which makes the emission factors less dependent on the average velocity alone. In particular, the reduced velocity on the motorways, still above 50 km/h, increases the dynamics in motorway driving. This type of driving dynamics is the result of the onset of congestion, where cycles of acceleration and deceleration occur. Consequently, effects from reduced speed limits on the motorway are, for example, expected to be somewhat smaller, as part of the emissions result from dynamic driving.

Major cities are incorporated several times in the typical trips, smaller cities are included fewer times, but do add up to about half of the urban driving. The trip length ensures a proper representation of urban, rural, and motorway driving in the total data. Navigation equipment is used for the actual route. The fraction of rural driving is somewhat lower than expected. This may in part be due to the definition of urban, rural, and motorway, based on the road maintainers from the national road database, instead of speed limits or road signs. However, an additional route was designed to enhance the rural velocity data.

These results apply to passengers cars and vans. A similar study must be carried out for trucks as well, as there is very limited, and largely outdated information on the driving behaviour of trucks in the Netherlands.

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A Driving behaviour vectors

A.1 Current driving behaviour from this study

	q1	q2	q3	q4	q5	q6	q7	q8	q9	q10
WS1	147.95	148.29	73.64	12.67	4.51	3.84	0.49	0.00	0.00	0.00
WM1	36.10	97.46	57.88	11.22	13.01	11.13	1.50	0.06	0.04	0.00
WF1	6.21	43.54	28.89	6.05	30.41	26.77	3.28	2.41	1.80	0.12
WT1	39.93	76.37	44.39	8.56	21.28	18.63	2.32	1.38	1.03	0.07
WT2	6.93	19.57	12.27	2.92	30.28	28.37	3.61	11.34	8.37	0.33
WT3	1.47	5.07	2.81	0.58	5.71	5.51	0.88	29.05	28.61	3.39
WS3	36.49	125.55	69.53	14.23	0.00	0.00	0.00	0.00	0.00	0.00
W80MSH	0.00	3.31	1.88	0.40	31.83	31.38	4.21	9.39	6.22	0.21
W80ZSH	0.00	3.31	1.88	0.40	18.71	18.45	2.48	21.48	16.59	0.83
W100MSH	0.00	3.31	1.88	0.40	9.89	9.62	1.51	28.17	23.28	1.08
W100ZSH	0.00	3.31	1.88	0.40	7.59	7.39	1.16	28.98	26.02	2.05
W120	0.00	3.31	1.88	0.40	3.33	3.28	0.60	30.58	30.74	3.82
W130	0.00	3.31	1.88	0.40	3.07	2.98	0.59	29.58	31.37	4.73

A.2 Previous driving behaviour as used in 2015 and before

	q1	q2	q3	q4	q5	q6	q7	q8	q9	q10
WS1	80.00	180.00	100.00	10.00	0.00	0.00	0.00	0.00	0.00	0.00
WM1	30.00	110.00	60.00	8.00	0.00	0.00	0.00	0.00	0.00	0.00
WF1	10.00	70.00	45.00	7.50	25.00	15.00	2.00	0.00	0.00	0.00
WT1 (WM1)	*30.00*	*110.00*	*60.00*	*8.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
WT2	3.25	6.50	4.00	1.50	35.00	30.00	5.00	1.25	0.70	0.00
WT3	2.50	20.00	4.50	0.12	2.36	2.30	0.30	32.00	32.00	1.00
WS3	31.00	235.00	62.00	2.30	3.40	2.90	0.36	0.00	0.00	0.00
W80MSH	0.00	0.00	0.00	0.00	23.10	25.80	0.05	21.90	14.20	0.00
W80ZSH	-	-	-	-	-	-	-	-	-	-
W100MSH	0.00	0.81	0.48	0.02	1.43	1.31	0.15	35.13	31.08	0.16
W100ZSH	0.00	0.81	0.48	0.02	2.27	2.11	0.26	34.79	30.57	1.16
W120	0.00	0.81	0.48	0.02	2.02	2.01	0.30	30.71	33.36	4.07
W130	0.00	0.24	0.14	0.01	0.59	0.58	0.09	29.48	35.21	6.31

In the past the manually added category motorway speed limit of 80 km/h without strict enforcement (W80ZSH) was an average of the W80MSH and W100MSH. There has been no underlying velocity data, but it was a constructed traffic situation. With the recent study, the driving behaviour of W80ZSH can be added in its own right.

Moreover, the urban average WT1 was in the past identical to urban normal WM1 from the lack of relative contributions of congestion levels to the average urban driving behaviour.

A.3 Descriptions of underlying traffic situations

Table 6 Definitions of the different traffic situations for which driving behaviour and emission factors are determined.

name	**Description**
WS1	Urban congestion, below 15 km/h, 10 stops per kilometre
WM1	Urban normal, 15-30 km/h average, 2 stops per kilometre
WF1	Urban free flow, 30-45 km/h, 1.5 stop per kilometre
WT1	Urban average, for the total national urban emissions
WT2	Rural roads, 60 km/h average, for national rural emissions
WT3	Motorway average, for the total national motorway emissions
WS3	Motorway congestion, average driving below a velocity of 50 km/h
W80MSH	Motorway 80 km/h speed limit with strict enforcement
W80ZSH	Motorway 80 km/h speed limit without strict enforcement
W100MSH	Motorway 100 km/h speed limit with strict enforcement
W100ZSH	Motorway 100 km/h speed limit without strict enforcement
W120	Motorway 120 km/h speed limit (maximum Dutch speed limit prior 2011)
W130	Motorway 130 km/h speed limit (maximum Dutch speed limit since 2011)

A.4 Determination of the driving vector from velocity data

Variables: **v(i)**: velocity [km/h] time series at 1 Hz, **a(i)** acceleration time series at 1Hz, **w**: contour lines related to power, **q(i,10)** driving vector times series at 1Hz. The total driving behaviour vector is the sum over the times series. The natural unit is seconds, conversion to s/km is by dividing with velocity.

```
 w = a(i) + 0.014*v(i);
 if v(i) < 50
   if v(i) < 5 && a(i) < 0.5
     q(i,1) = 1.0;
   else
     q(i,2) = 1.0;
     if w > 0
        q(i,3) = w;
        if w > 1.0
            q(i,4) = w - 1.0;
        end
     end
   end
 end
 if v(i) >= 50 && v(i) < 80
    q(i,5) = 1.0;
    if w > 0
      q(i,6) = w;
      if w > 1
          q(i,7) = w - 1.0;
      end
    end
 end
 if v(i) >= 80
    q(i,8) = 1;
    if w > 0.5
      q(i,9) = w - 0.5;
      if w > 1.5
          q(i,10) = w - 1.5;
      end
    end
 end
end
```