# Real-world driving behaviour on 80 km/h Dutch motorways with and without speed enforcement

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**Mobility & Built Environment**
www.tno.nl
+31 88 866 00 00
info@tno.nl

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| Author(s) | J.M. (Jessica) de Ruiter, A. (Aspasia) Panagiotidou, T. (Thomas) Frateur, Y. (Zakaria) Boukallouht |
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# Summary

Driving behaviour on Dutch motorways with an 80 km/h speed limit without strict enforcement remains largely unexplored, not only compared to 80 km/h roads with strict enforcement, but also 100 km/h roads under both conditions. Understanding these behaviours is crucial, as drivers' actions directly influence vehicle dynamics, which in turn impact emissions. Current emission factors for these road segments are based on expert judgement informed by the motorway driving data that was available at the time (Ligterink, 2016; Ligterink *et al.*, 2009); this data did not specifically differentiate roads that were 80 km/h with or without enforcement.

In September 2024, TNO carried out a measurement campaign for the Ministry of Infrastructure and Water Management to investigate real-world driving behaviour on Dutch motorways with an 80 km/h speed limit, both with and without speed enforcement. The primary objective was to gain insights into the driving patterns and associated emission factors on these roads.

The campaign involved tracking Dutch light-duty traffic using a specially equipped measurement vehicle on the A9 and A10 highways near Amsterdam. Both highways have a speed limit of 80 km/h, but enforcement differs: the A9 lacks strict enforcement (SRM emission factor 80 ZSH), while the A10 is strictly monitored for compliance (SRM emission factor 80 MSH). By utilising the speed of the measurement vehicle, a front-mounted radar, and a license plate camera accurate estimations of the speed and acceleration profiles of the followed vehicles were made. This data was then compared with data from a previous campaign on roads with an 100 km/h speed limit and no enforcement (SRM emission factor 100 ZSH), to gain insights into the emission factors of the roads under investigation. Additionally, to ensure the campaign's data was representative of the long-term driving patterns recorded over the year, it was compared with data from inductive loops embedded in the respective roads.

The results indicated a clear difference in driving behaviour between the two highways, with speed enforcement on the A10 leading to higher compliance. This is in agreement with conclusions from previous analyses. Furthermore, driving behaviour in this work on roads with 80 km/h speed limits and no speed enforcement was found to be similar to the behaviour in previous work on roads with 100 km/h and no speed enforcement. As a result, we recommend updating the emission factors for 80 km/h roads without speed enforcement (80 ZSH) to match those of roads with a 100 km/h speed limit under similar conditions (100 ZSH): the current light-duty $NO_x$ SRM emission factors 100 ZSH are around 5% higher than the old 80 ZSH and around 20% higher than that for 80 MSH. Implementing this recommendation currently has no effect on Dutch total annual emissions, due to the negligible number of travel kilometres on 80 km/h roads without enforcement (80 ZSH).

Considering the current (relatively limited) number of motorway roads assigned 80 ZSH we do recommend further research if significantly more roads are designated 80 ZSH in the future.

# Contents

# 1 Introduction

Driving behaviour on Dutch motorways with an 80 km/h speed limit without strict enforcement remains largely unexplored, not only compared to 80 km/h roads with strict enforcement, but also 100 km/h roads under both conditions. Understanding these behaviours is crucial, as drivers' actions directly influence vehicle dynamics, which in turn impact emissions. Current emission factors for these road segments are based on expert judgement informed by the motorway driving data that was available at the time (Ligterink, 2016; Ligterink *et al.*, 2009), which did not specifically differentiate roads that were 80 km/h with or without enforcement.

This study focussed on analysing driving behaviour on 80 km/h motorways with and without strict enforcement to refine emission factors and improve traffic-related air quality assessments. To achieve this, a specially instrumented vehicle was used to track Dutch traffic, specifically passenger cars and vans, on two selected motorway sections: the outer lanes of the A9 near Diemen (80 km/h limit, no speed enforcement) and the A10-West (80 km/h limit, strict enforcement). Using the measurement vehicle's speed, a front-mounted radar, and a license plate camera, accurate estimates of speed, acceleration, and vehicle type of the followed vehicles were obtained. The campaign lasted four days (16th-19th of September 2024), resulting in a total of 34 hours of driving.

To get insights into the emission factors of the roads under investigation, measurement data of the aforementioned campaign was compared with data collected through a previous campaign on roads with a 100 km/h speed limit (Ligterink, 2016; Vroom *et al.*, 2023). Additionally, the collected data was compared with data from induction loops embedded in these segments throughout 2023 to assess how well the short-term observations align with the long-term driving patterns recorded over the year.

The measurement campaign conducted by TNO in September 2024 was part of the research program Emission Measurements - Factors - Particulate Matter 2024, funded by the Ministry of Infrastructure and Water Management.

The remainder of this report is organised as follows:

- Section 2 presents the measurement results, starting with general observations and followed by a detailed analysis of the results under both strict and non-strict enforcement conditions.
- Section 3 summarises the key findings and conclusions, emphasising the implications of the results.
- Appendix A provides a detailed description of the methodology used throughout the study, covering the measurement setup, the selection of test locations, the conditions under which the tests were conducted, and the specific testing rules followed to ensure consistency and accuracy.
- Appendix B details the data (pre)processing steps as well as a brief summary of the collected measurement data including the followed vehicle categories and fuel types.
- Appendix C includes a range of supplementary information, including the daily speed profiles, various statistics of the speed and acceleration profiles, and a detailed comparison with previous studies on motorway behaviour without speed enforcement.

# 2 Measurement results

The measurement campaign took place over four days, from September 16 to 19, 2024, along the A9 and A10 highways, as shown in Figure 2.1. On the A9, measurements were taken in the outer lanes, where the speed limit is 80 km/h, matching the speed limit on the A10. The key distinction between the two highways is that while there is no speed limit enforcement on the A9, the A10 is strictly monitored for compliance.

Data was collected during both daytime (06:00–19:00) and nighttime (19:00–06:00).[1] A total of 196 vehicles were measured, with 153 tracked during the daytime (98 on the A9 and 55 on the A10) and 43 during the nighttime (22 on the A9 and 21 on the A10). The entire campaign lasted 34 hours. The measurement set-up and data processing are described in Appendix A and Appendix B respectively. More information regarding the followed vehicle categories and fuel types are noted in Table B.1 –Table B.4.

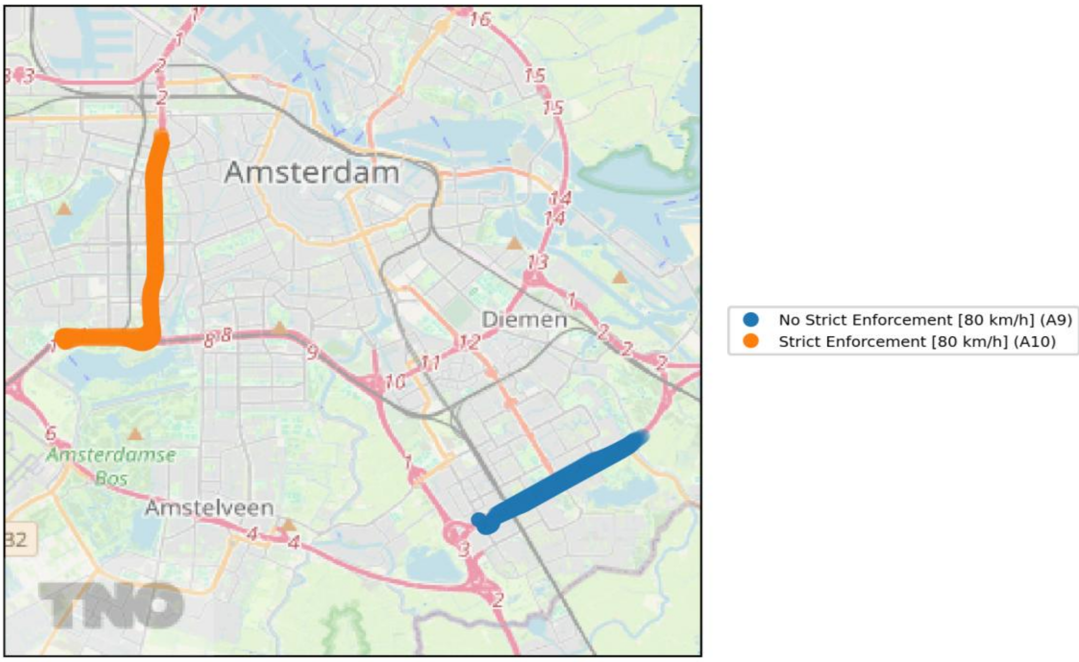


Figure 2.1: Measurement locations on highways near Amsterdam with an 80 km/h speed limit, both with and without strict enforcement.

This study also involved comparing the driving behaviour observed on the A9 highway (80 km/h speed limit and no enforcement) with data from a previous measurement campaign on roads with a 100 km/h speed limit, also without speed enforcement (Vroom *et al.*, 2023).

[1] This distinction is made due to the variation in observed speeds on motorways in previous work, as well as the time-dependent motorway speed limits (100 km/h 06:00-19:00, 130 km/h 19:00 – 06:00) on various roads in the Netherlands which may influence driving behaviour on these trajectories.

We therefore build on previously acquired knowledge to offer a better understanding of how similar conditions influence driving behaviour and, consequently, emissions.

## 2.1 Factors influencing vehicle tracking: challenges and observations

Driver observations during vehicle tracking on the A9 (No Speed Enforcement) and A10 (speed enforcement) highways highlighted several factors influencing the recorded results.

On the A9, the relatively short routes limited the chase car's ability to follow vehicles for the full minimum duration initially planned (see also Appendix A for testing rules). Additionally, low traffic volume made it difficult to track vehicles effectively, and most vehicles consistently exceeded the 80 km/h speed limit, further complicating the tracking process. A significant number of vehicles were travelling at speeds which were so high it made them impossible to follow safely. Speed distributions in this report therefore lack these excessive speeds. Unfortunately, with the current chase-car driver interface it was not possible for the driver to record the precise number of vehicles that could not be followed due to excessively high speeds. This will be developed further for future campaigns.

Throughout the campaign, approximately eight times, drivers of the followed vehicles became aware they were being tracked, resulting in the respective measurements being broken off and the need to restart tracking with new vehicles. Moreover, license plate recognition proved difficult in the low-light conditions inside tunnels.

On the A10, while traffic was heavier, frequent lane changes still made it difficult to track vehicles for the preferred minimum duration. However, the speed limit was generally adhered to (unlike on the A9) making vehicle tracking somewhat easier.

## 2.2 Strict enforcement leads to significantly higher compliance

The driving behaviour on the A9 highway is compared to that on the A10 highway, which features an 80 km/h speed limit and strict enforcement. Both distributions are also compared with data collected throughout 2023 via inductive loops to assess whether the campaign data accurately reflect long-term driving patterns.

Figure 2.2 shows the speed patterns for both road types during daytime and nighttime measurements. The distributions under enforcement conditions exhibit a sharper cutoff compared to those without enforcement, suggesting greater driver compliance with the speed limit. Note that although Figure 2.2 shows both daytime and nighttime distributions, the rest of the analyses focus solely on daytime measurements. This decision was made based on the similarity of both distributions, and the availability of data from the different data sources used for comparison.

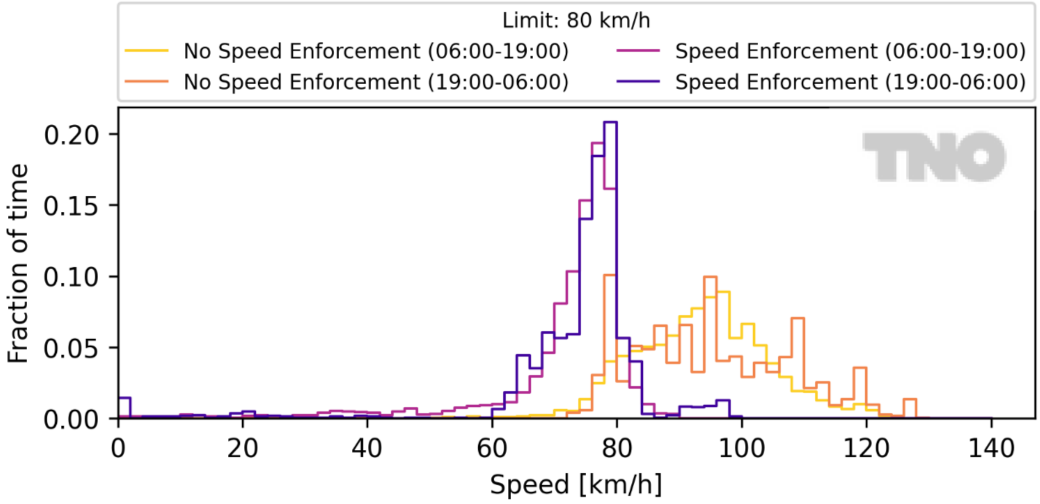


Figure 2.2: Speed distributions from data collected during the measurement campaign on the A9 (80 km/h, No Speed Enforcement) and A10 (80 km/h, Speed Enforcement) highways, covering both daytime and nighttime measurements.

Figure 2.3 demonstrates the overlap with the measurement data and inductive loop data, indicating that the behaviours observed in the measurement week are representative for the entire year. For the A9 (80 km/h, No Speed Enforcement), the higher frequencies observed at lower speed values can be attributed to the chase car's strict compliance with the speed limit on the first day of measurements. Note that the loop data also shows a more localised peak which may be attributed to the nature of loops which record average speeds over a certain distance, while the instantaneous driving speed recorded by the chase car fluctuates over the duration of the measurement. Changes in these instantaneous speeds (i.e. acceleration) are often the most relevant with respect to emissions, which reinforces the need for these measurements.

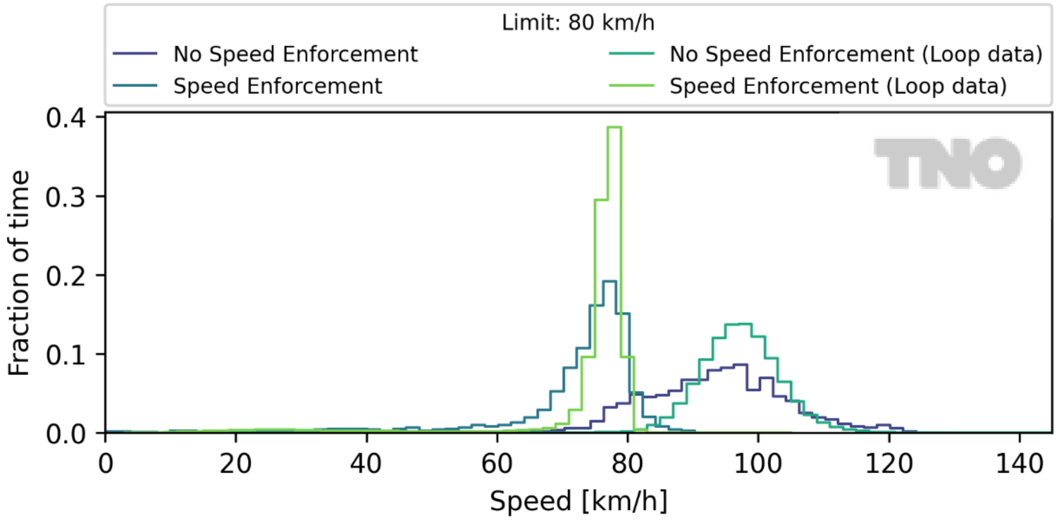


Figure 2.3: Speed distributions based on data collected from two sources: 1) measurements from this year's measurement campaign on the A9 (80 km/h, no speed enforcement) and A10 (80 km/h, speed enforcement), and 2) data gathered for the whole year of 2023 from inductive loop detectors embedded on the respective road segments. Speed distributions for both highways align closely with those emerging from the data of the inductive loops, suggesting that the driving patterns observed during the measurement campaign accurately reflect the long-term driving behaviour recorded over the year.

The speed distribution on 80 km/h roads with speed enforcement closely mirrors that observed on motorways (with enforcement only) in previous research by Vroom et al. (2023), in which chase car data was compared with monitoring data for both 80 km/h rural roads and motorways. Considering the findings of that study—both regarding the data on 80 km/h motorways and the comparison between 100 km/h roads with and without speed enforcement—this new analysis further highlights the effectiveness of speed enforcement as a measure to encourage speed limit compliance.

## 2.3 80 km/h and 100 km/h roads without enforcement show similar driving behaviour

By comparing driving behaviour with data from other roads with similar enforcement conditions and known emissions, we can gain insights into the expected emissions. Here we compare the speed and acceleration distributions on the A9 with data collected in 2022 for road sections with a 100 km/h speed limit without strict enforcement (Vroom *et al.*, 2023). The speed distribution was also compared to the yearly average speed distribution obtained by inductive loop measurements at the A9.[2]

Figure 2.4 illustrates that all three speed distributions are aligned around the same point. A closer comparison between the speed profile determined in this work (80 km/h) and on roads with 100 km/h speed limits reveals more congestion on the latter. This finding aligns with the driver's reports of light traffic during the 2024 campaign and frequent instances of vehicles exceeding the speed limit on the A9.

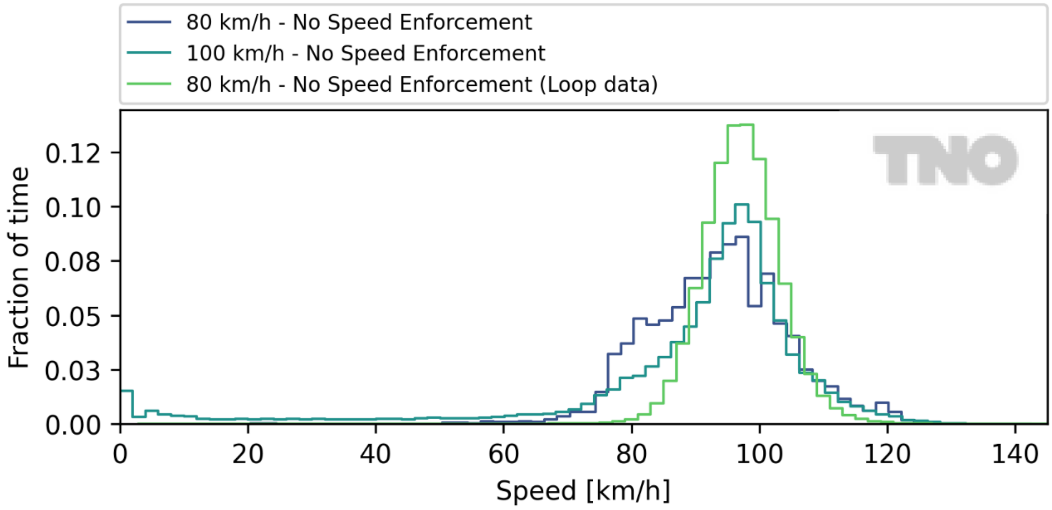


Figure 2.4: Speed distributions from the following three sources: 1) the measurement campaign on the A9 highway with 80 km/h speed limit and no speed enforcement), 2) the 2022 campaign on roads with a 100 km/h speed limit and no speed enforcement (Vroom *et al.*, 2023), and 3) the inductive loop detectors on the A9 collecting data throughout 2023.

The acceleration distributions for both the A9 (80 km/h) and 100 km/h speed limits, as shown in Figure 2.5, appear to be centred around the same point.

[2] To ensure consistency and based on the availability of data from all sources, all figures represent daytime measurements.

However, the distribution for the 100 km/h speed limit has a slightly higher range, indicating variability and more dynamic driving. This difference could be attributed to the varying traffic conditions during the two campaigns. Specifically, roads with a 100 km/h speed limit indicated higher congestion levels and more frequent instances of vehicles driving at lower speeds allowing for greater acceleration. In contrast, traffic on the A9 was much lighter, and vehicles were driving at higher speeds, potentially facing physical limitations in terms of available power for acceleration (Ligterink, 2016) or having less cause to accelerate.

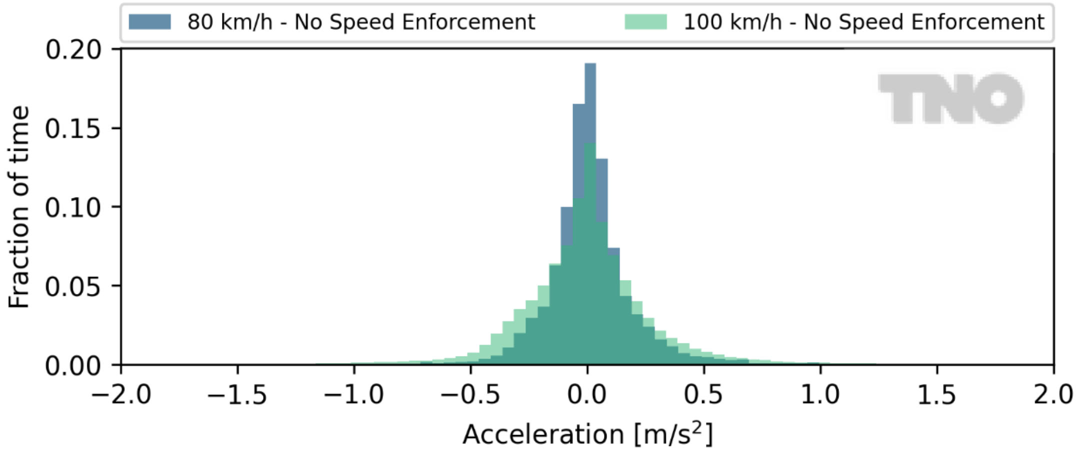


Figure 2.5: Acceleration distributions from the following two sources 1) data collected during the measurement campaign on the A9 highway (80 km/h, no speed enforcement), and 2) data collected during the 2022 campaign on roads with a 100 km/h speed limit and no enforcement(Vroom *et al.*, 2023). Both distributions appear to be centred around the same point. However, acceleration range is slightly higher on roads with 100 km/h speed limit indicating dynamic driving.

Figure 2.6 displays the two-dimensional normalized frequency of various speed–acceleration combinations on roads with speed limits of 80 km/h and 100 km/h. As discussed above there is a strong overlap in driving behaviour, though the A9 does display less stagnation (low velocity) and a more localised peak. As previously mentioned, this is likely due to the limited traffic observed on the A9 during the campaign measurements, as well as an order of magnitude difference in the amount of data that was collected.

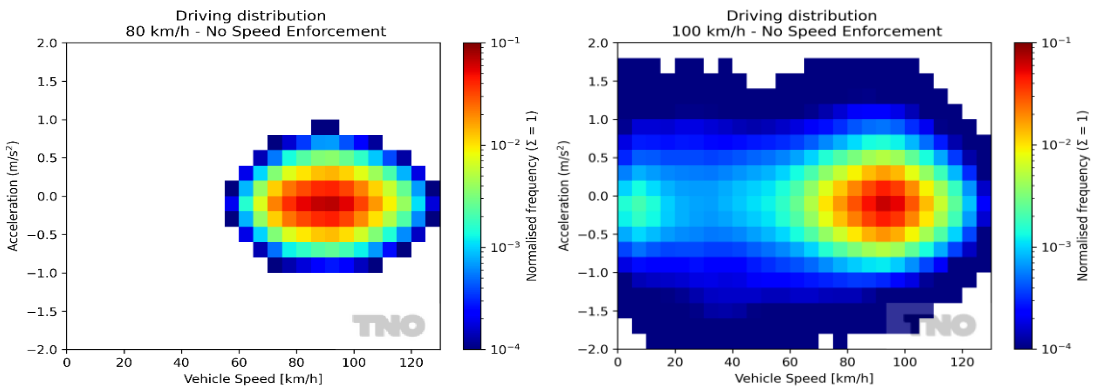


Figure 2.6: Normalized frequency of acceleration and vehicle speed for the A9 highway with an 80 km/h speed limit and no enforcement (left side), and roads with a 100 km/h speed limit and no enforcement (right side)(Vroom *et al.*, 2023). In both figures, dark red indicates the most frequent occurrences. Driving on roads with an 80 km/h speed limit shows less dynamic behaviour compared to roads with a 100 km/h speed limit, as evidenced by the narrower speed and acceleration ranges.

The results indicate that the driving behaviour observed on the A9 and that on roads with 100 km/h speed limits without enforcement exhibits similar patterns. It is important to note that the driving behaviour used for the estimation of emission factors for 80 km/h motorways without speed enforcement was based on expert judgement due to the lack of 80 km/h without enforcement specific velocity data (Ligterink, 2016): behaviour on motorways with 80 km/h (with speed enforcement) and 100 km/h (both with and without enforcement) limits were used to infer the relevant driving behaviour and the resulting emission factors.

To quote explicitly from (Ligterink, 2016):

- 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).

Considering the above analysis, it is clear that 80km/h without speed enforcement behaviour shows a stronger overlap with 100 km/h without speed enforcement than previously assumed (see also Appendix C.3 for an extended analysis). There does not seem to be evidence in the current campaign for the previous truncation of speeds to 90km/h. However, we do note that this conclusion is based on the currently available data as driven in the current campaign. If more roads are designated 80 km/h without enforcement, we recommend that follow-up measurements are performed.

## 2.4 Updated $NO_x$ emission factor 80 ZSH is 20% higher than 80 MSH

For the calculation of emissions in the Dutch Emission Inventory (Emissieregistratie, 2025) it is assumed that no kilometres are driven on motorways with a speed limit of 80 km/h without strict enforcement. Therefore, changing the SRM 80 ZSH emission factor has no effect on current Dutch annual emission totals.

However, considering that:

- there is a strong overlap in driving behaviour observed on 80 km/h and 100 km/h roads without speed enforcement, and
- the previous 80 ZSH emission factor was based on expert judgement due to the lack of specific velocity data (Ligterink, 2016), and
- there is significantly more emission monitoring data underpinning the 100 ZSH emission factors,

we recommend the 80 ZSH SRM emission factors to be set equal to the current 100 ZSH SRM emission factors. If the 80 ZSH regime were to be implemented on roads with higher traffic flows, it would also likely lead to an increased fraction of time with lower driving speeds as observed for 100 ZSH due to increased congestion because of these higher traffic flows.

In Table 2.1 we compare the light-duty 2025 SRM motorway emission factors for the year 2024 (TNO, 2025). Although the current $NO_x$ emission factor for 80 ZSH would only increase 4% when set equal to 100 ZSH, the difference with 80 MSH would increase to 20%.

For the other pollutants we do not observe a generic difference between 100 ZSH and 80 ZSH: $CO_2$ emissions are lower under 80 ZSH, while the particulate emissions are higher (see also Section C.3 for a more detailed comparison of the differences in behaviour which may influence this).

Table 2.1: Comparison of the light-duty SRM motorway emission factors for 2024 (TNO, 2025) for roads with a speed limit of 100 km/h without speed enforcement (100 ZSH) to those for 80 km/h without speed enforcement (80 ZSH) and 80 km/h with speed enforcement (80 MSH).

| | 100 ZSH relative to 80 ZSH | 100 ZSH relative to 80 MSH |
|---|---|---|
| $NO_2$ | 4.4% | 34% |
| $CH_4$ | -24% | 23% |
| $NO_x$ | 4.2% | 20% |
| EC | 13% | 20% |
| $RWCO_2$ | -5.0% | 16% |
| $CO_2eq$ | -4.6% | 15% |
| $PM_{2.5}$ (total) | 5.3% | 11% |
| $NH_3$ | 6.9% | 9% |
| $PM_{10}$ (total) | 1.2% | 3.1% |
| $N_2O$ | 0.0% | 0.0% |
| VOS (exhaust) | -2.3% | -0.8% |
| CO | 0.4% | -6.3% |

# 3 Conclusions and recommendations

A chase car campaign has been performed to investigate the driving behaviour on 80 km/h motorways, both with and without speed enforcement. Measurements were conducted on stretches of the A9 and A10 near Amsterdam over a period of four days, following a total of 196 vehicles and collecting 34 hours of behaviour data.

On the A9 (80 km/h without speed enforcement) most vehicles consistently exceeded the 80 km/h speed limit. A significant number of vehicles were travelling at speeds which were so high it made them impossible to follow safely. Speed distributions in this report therefore lack excessive speeds. With the current chase-car driver interface it was not possible for the driver to record the precise number of vehicles that could not be followed due to this, but this will be developed further for future campaigns.

A clear difference in driving behaviour was seen between the A9 and A10. Together with previous analyses this shows that speed enforcement leads to significantly higher compliance compared to the 80 km/h speed limit. This further supports the effectivity of speed enforcement as a traffic measure.

80 km/h and 100 km/h roads without enforcement show similar driving behaviour. The driving behaviour observed in this campaign was compared to data collected in the 2022 chase car campaign for 100 km/h roads without enforcement which shows strong overlap. For this reason, we recommend that the relevant SRM emission factor (80 ZSH) be increased to match that for 100 km/h roads without enforcement (100 ZSH). Considering the current (relatively limited) number of motorway roads assigned 80 ZSH we recommend further research if significantly more roads are designated 80 ZSH in the future.

For the calculation of emissions in the Dutch Emission Inventory it is assumed that no kilometres are driven on motorways with a speed limit of 80 km/h without strict enforcement. Therefore, changing the SRM 80 ZSH emission factor has no effect on current Dutch annual emission totals. The current light-duty $NO_x$ SRM emission factors 100 ZSH are only around 5% higher than the old 80 ZSH, but this is around 20% higher than 80 MSH.

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# Signature

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| Jan Hoegee<br>Research manager | Jessica de Ruiter<br>Author |

# Appendix A
# Chase car methodology and instrumentation

## A.1 Driver behaviour definitions

Driver behaviour is a set of properties defining the way a certain vehicle is driven by its driver. In this study, driver behaviour is captured by the velocity and acceleration of the vehicle over a longer period of time. It is worth noting that driver behaviour can also be influenced by vehicle properties such as engine power and vehicle mass. These influences are not considered explicitly in this study due to the relatively small sample size and investigated roads.

## A.2 Measurement setup

The measurement setup used in this study is devised to efficiently capture driving behaviour of multiple vehicles over a longer period of time. The setup is based around a chase car equipped with measurement equipment and measurement management software.
The chase car is used to chase randomly selected vehicles on selected roads to enable long duration measurements of speed and acceleration on the chased vehicle.

The platform used for the chase car is a Volkswagen ID7 PRO electric vehicle with 210kW installed power to ensure all randomly selected vehicles can be followed.

The chase car is equipped with:

- a radar[3] for relative speed and acceleration measurements.
- a VBOX[4] with CANBUS connection for inertial measurements and CANBUS readout of the ABS speed signal for absolute speed measurements of the chase car.
- an ANPR camera[5] for automated license plate scanning.
- a SEMS data logger to continuously log all relevant signals.
- an operator interface with hardware input buttons and visualisations of the logged data to facilitate starting and stopping individual measurements on chased vehicles.

The operator interface consists of a laptop with custom user interface UI software and a numeric keyboard in reach of the chase car operator. The UI software indicates the speed of the followed vehicle, the objects in view of the radar, the status of the measurement and available license plates from the ANPR camera as shown in Figure A.1. Hardware inputs are available to the chase car operator to start, pause and stop the measurement of an individual vehicle, and to select the valid license plate for each measurement.

[3] Continental ARS 309-2 Long Range Radar Sensor
[4] VBOX Inertial Measurement 04-V2
[5] ARVOO DUO1200 ANPR camera & ITS502-GE processing unit

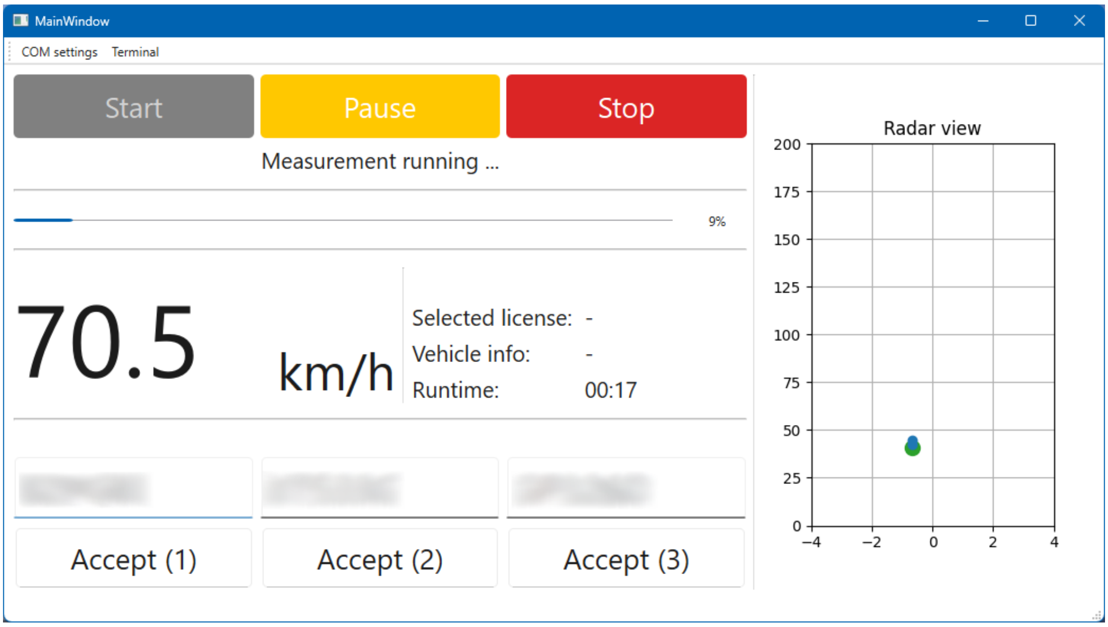


Figure A.1: Custom UI software as part of the operator interface (emulated data).

All equipment is connected through either CAN or serial connections to the SEMS data logger. A schematic representation of all instrument connections is shown in Figure A.2. Data is logged continuously at 1 Hz to a .csv file in SEMS. In addition, the UI software generates a copy of this log file with additional information on measurement statuses and measurement ID's. An additional log file is generated by the UI software to summarize measurement specific results such as duration of measurement, license plate and vehicle information.

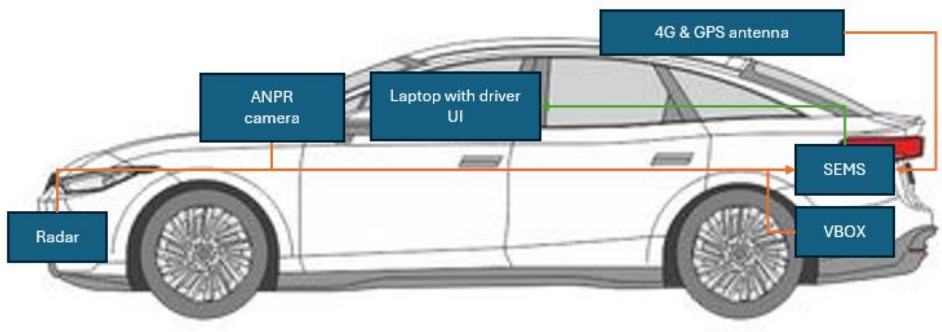


Figure A.2: Schematic representation of the chase car measurement setup and instrument connections.

# A.3 Test location & conditions

Driver behaviour measurements are conducted on highways with a minimum of two lanes in each direction with and without strict enforcement on 80 km/h to identify differences in driver behaviour on these roads. The period and conditions during which testing is performed needs to be representative for normal traffic conditions. Therefore, holiday periods and weekends are excluded from the test period. Testing however needs to capture both day and night conditions, and both high and low traffic conditions.

No specific testing limitations related to weather conditions are considered, however extreme weather conditions such as gale force wind, heavy downpours or icing are excluded from testing due to the increased safety risk and expected reduced representativity of the measured data.

## A.4 Testing rules

Tests are performed by driving back and forth on pre-defined road sections and following vehicles of interest. Vehicles are randomly selected with the aim to get a representative sample of the average Dutch fleet. Electric vehicles however have no priority in this study.

When a vehicle of interest is acquired, a test is started in the UI software while following this vehicle at a normal driving distance.

A vehicle is chased for preferably up to 3 minutes, the chase should however be broken off when:

- a vehicle cannot be followed due to excessive speeds.
- another vehicle merges in the same lane between the target vehicle and the measurement vehicle.
- the vehicle takes an exit from the pre-defined road section.

During the measurement, the chase car operator should select the matching license plate from the ANPR camera to the measurement using the provided interface buttons. The chase car operator should not significantly exceed the acting speed limits on the public road. For vehicles driving faster than the allowed speed, a measurement with runout is performed for the duration that the target vehicle remains in range of the chase car mounted radar.

After the preferred measurement duration has lapsed, or if the measurement is broken off due to one of the reasons stated above, the chase car operator can start the measurement of a new target vehicle.

# Appendix B
# Data (pre)processing steps and summary

After collection, the data is processed as follows:

- Filtering Measurement Data
  - SEMS data collected during the measurement campaign was filtered to retain only periods of active measurement, excluding any pauses or interruptions.
- Assigning Data to Road Segments
  - Each data point was mapped to its corresponding road segment based on latitude and longitude coordinates. For the A9 highway, where GPS gaps occurred due to the existing tunnel, missing coordinates were estimated using linear interpolation.
- Excluding Irregular Measurements
  - Measurements that were interrupted shortly after starting were deemed invalid and removed to ensure high data quality.
- Calculating Vehicle Velocity
  - The velocity of the followed vehicles was calculated by combining the rate of change of the recorded distance with the chase car's velocity, obtained from the ABS signal. In cases where more than 50% of the distance data for a followed vehicle was unavailable, the chase car's velocity was used as a substitute, as it closely reflected the driving behaviour of the followed vehicles.
- Computing Acceleration
  - Acceleration for both the chase car and followed vehicles was computed using the central difference method, which estimates the rate of change of velocity by calculating the difference between velocities at adjacent time steps and dividing by the time interval.

After excluding 4 invalid measurements, the final dataset included 192 vehicles. The vehicle categories and fuel types are detailed in Table B.1, Table B.2, Table B.3, Table B.4 below.

The average measurement duration per vehicle was 81 seconds on the A9 and 78 seconds on the A10, with the entire campaign lasting a total of 34 hours. Data was collected at a frequency of 1 Hz. At each time step, the recorded attributes included the speed of the chase car (derived from the wheel rotation velocity signal), its GPS coordinates (longitude and latitude), the distance between the chase car and the vehicles being followed, and the license plates of these vehicles. The license plate information was later used to obtain the vehicles' VERSIT+ classes and taxonomy codes, providing details such as the vehicle type and fuel.

# B.1 Vehicle categories and fuel types of followed vehicles

The tables below present detailed information on the vehicle categories and fuel types of the monitored vehicles during both daytime and nighttime measurements on the A9 and A10 highways.

Table B.1: Distribution of vehicle types by fuel category for daytime measurements on A9 (no strict enforcement, 80 km/h)

| | A9 (no strict enforcement, 80 km/h) – daytime measurements | | | | | |
|---|---|---|---|---|---|---|
| | Total | Diesel | Petrol | LNG | PHEV | EV |
| Passenger cars | 68 | 1 | 58 | - | 4 | 5 |
| Delivery vans | 7 | 5 | - | 1 | - | 1 |
| Unidentified | 20 | - | - | - | - | - |

Table B.2: Distribution of vehicle types by fuel category for nighttime measurements on A9 (no strict enforcement, 80 km/h)

| | A9 (no strict enforcement, 80 km/h) – nighttime measurements | | | | | |
|---|---|---|---|---|---|---|
| | Total | Diesel | Petrol | LNG | PHEV | EV |
| Passenger cars | 6 | | 6 | | | |
| Delivery vans | - | - | - | - | - | - |
| Unidentified | 16 | - | - | - | - | - |

Table B.3: Distribution of vehicle types by fuel category for daytime measurements on A10 (strict enforcement, 80 km/h)

| | A10 (strict enforcement, 80 km/h) – daytime measurements | | | | | |
|---|---|---|---|---|---|---|
| | Total | Diesel | Petrol | LNG | PHEV | EV |
| Passenger cars | 44 | 7 | 23 | - | 1 | 13 |
| Delivery vans | 6 | 5 | - | 1 | - | - |
| Unidentified | 4 | - | - | - | - | - |

Table B.4: Distribution of vehicle types by fuel category for nighttime measurements on A10 (strict enforcement, 80 km/h)

| | A10 (strict enforcement, 80 km/h) – nighttime measurements | | | | | |
|---|---|---|---|---|---|---|
| | Total | Diesel | Petrol | LNG | PHEV | EV |
| Passenger cars | 6 | 1 | 5 | - | - | - |
| Delivery vans | 1 | 1 | - | - | - | - |
| Unidentified | 14 | - | - | - | - | - |

# Appendix C
# Supplementary information

## C.1 Speed profiles from daytime measurements for each day of the measurement campaign

The following figures present the speed distributions of the vehicles monitored during daytime measurements for both the A9 and A10 highways, presented separately for each day of the campaign. Note that the actual tracking duration is significantly shorter than the total driving hours of the campaign because of the short road stretches and the time required to loop around. Additionally, on the first day of measurements the chase car was given explicit instructions to adhere to the road's speed limit; in the following days these instructions were altered to 'safe participation in the surrounding traffic'.

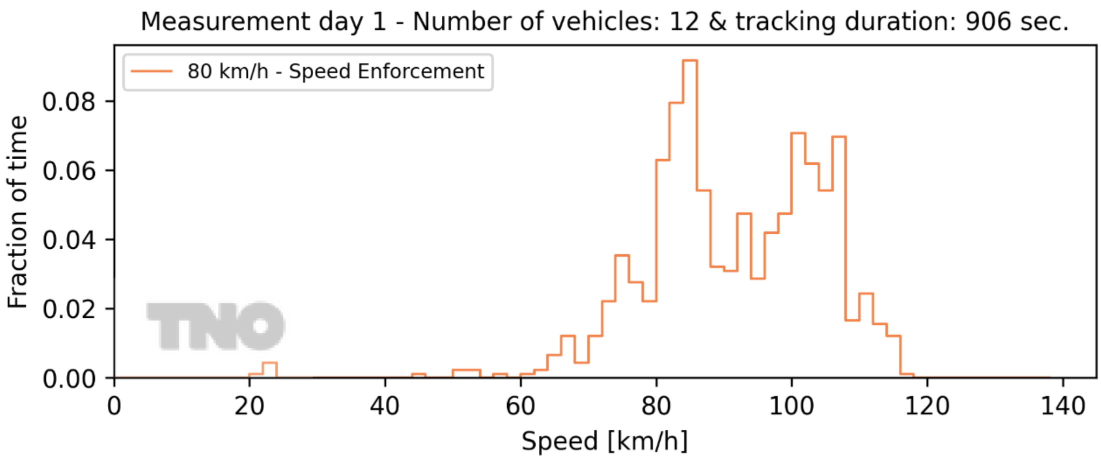


Figure C.1: Speed distribution of daytime measurements during the first day of the measurement campaign on the A9 highway (80 km/h speed limit, no speed enforcement).

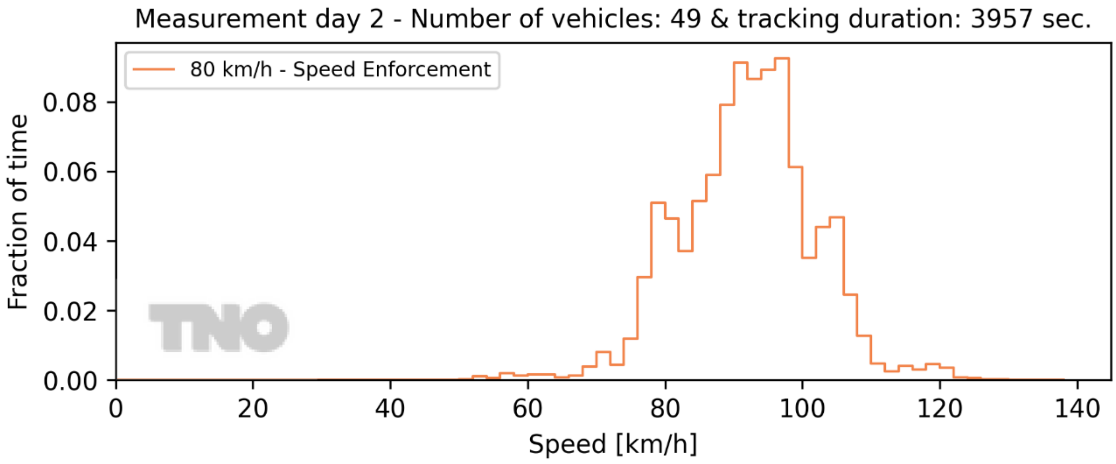


Figure C.2: Speed distribution of daytime measurements during the second day of the measurement campaign on the A9 highway (80 km/h speed limit, no speed enforcement).

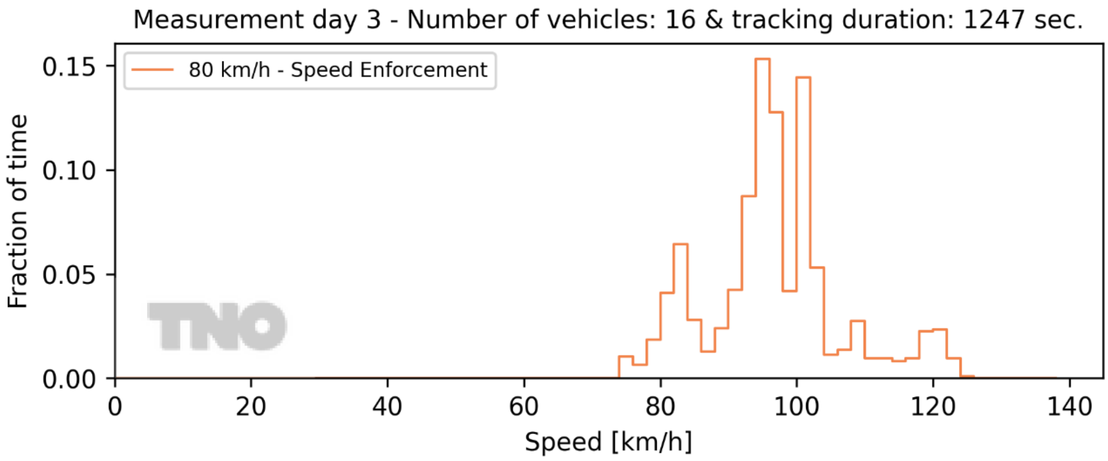


Figure C.3: Speed distribution of daytime measurements during the third day of the measurement campaign on the A9 highway (80 km/h speed limit, no speed enforcement).

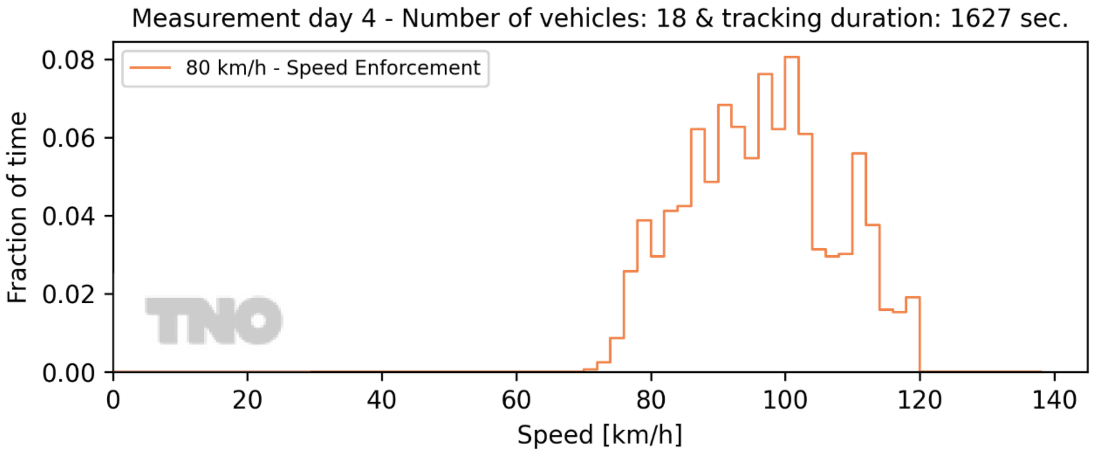


Figure C.4: Speed distribution of daytime measurements during the fourth day of the measurement campaign on the A9 highway (80 km/h speed limit, no speed enforcement).

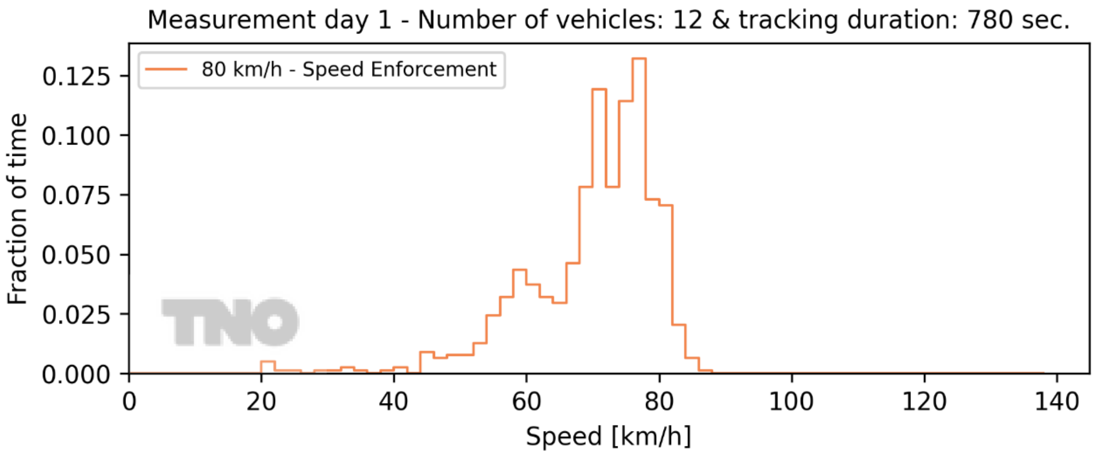


Figure C.5: Speed distribution of daytime measurements during the first day of the measurement campaign on the A10 highway (80 km/h speed limit, speed enforcement).

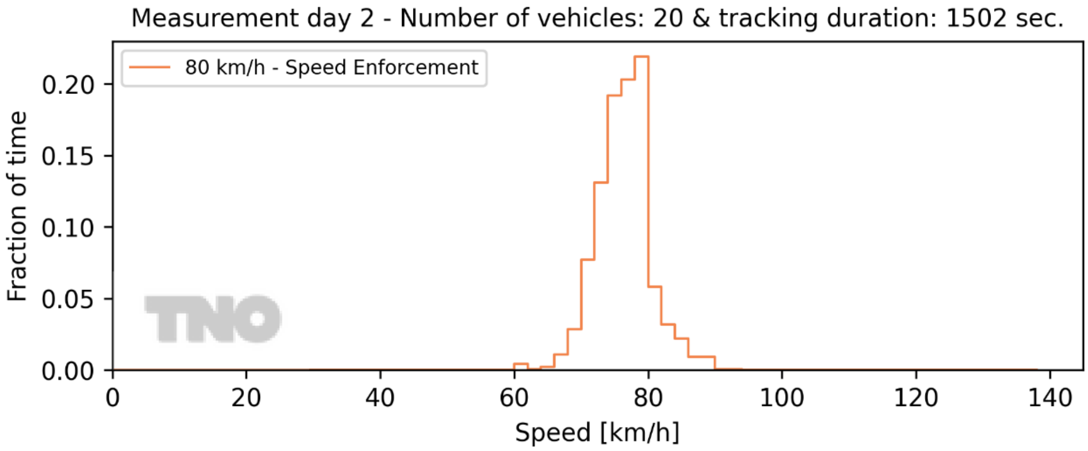


Figure C.6: Speed distribution of daytime measurements during the second day of the measurement campaign on the A10 highway (80 km/h speed limit, speed enforcement).

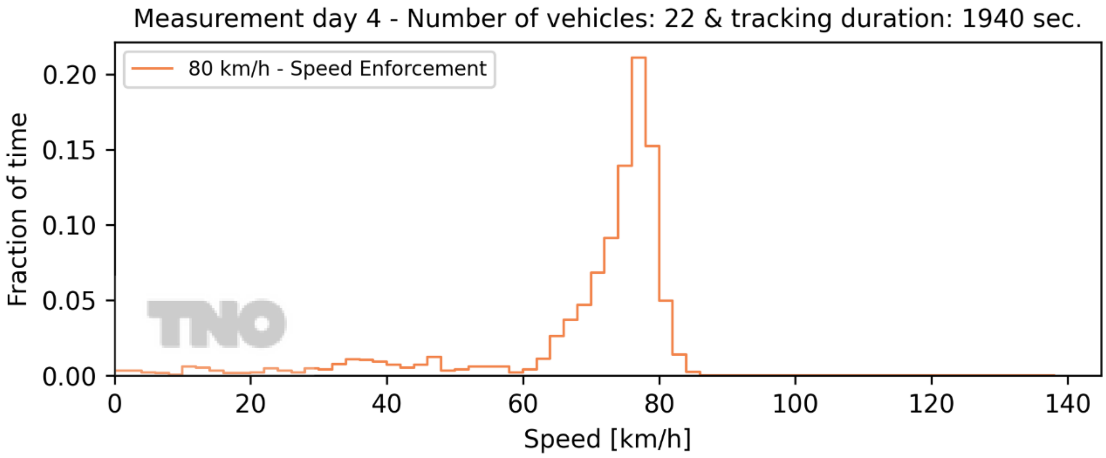


Figure C.7: Speed distribution of daytime measurements during the fourth day of the measurement campaign on the A10 highway (80 km/h speed limit, speed enforcement).

## C.2 Statistic metrics for speed and acceleration profiles for roads with different speed limits and enforcement conditions

Table C.1: Statistic metrics for speed and acceleration distributions for roads with 80 km/h / 100 km/h speed limit and different enforcement conditions.

| | 80 km/h – no speed enforcement | 80 km/h – speed enforcement | 100 km/h – no speed enforcement |
|---|---|---|---|
| Mean speed [km/h] | 93.58 | 71.84 | 88.19 |
| Standard deviation for speed values [km/h] | 10.75 | 12.34 | 23.48 |
| Mode value – speed [km/h] | 95.48 | 76.84 | 97.28 |
| Mean acceleration [m/s^2] | 0.017 | -0.008 | -0.006 |
| Standard deviation for acceleration values [m/s^2] | 0.199 | 0.273 | 0.317 |
| Mode value – acceleration [m/s²] | 0.002 | 0.017 | 0.002 |
| Q1 25$^{th}$ percentile – speed [km/h] | 86.37 | 70.9 | 85.55 |
| Q2 50$^{th}$ percentile – speed [km/h] | 93.97 | 75.39 | 94.82 |
| Q3 75$^{th}$ percentile – speed [km/h] | 100.79 | 78.10 | 100 |
| Q1 25$^{th}$ percentile – acceleration [m/s²] | -0.072 | -0.111 | -0.142 |
| Q2 50$^{th}$ percentile – acceleration [m/s²] | 0.003 | 0.003 | 0 |
| Q3 75$^{th}$ percentile – acceleration [m/s²] | 0.085 | 0.103 | 0.123 |

## C.3 Driving behaviour on roads with 80 km/h and 100 km/h speed limits under no enforcement conditions

The difference between the driving behaviour on 80 km/h and 100 km/h motorways without speed enforcement as discussed in Section 2.3 is shown in Figure C.8. This figure highlights the differences in these frequencies between the two road types. Blue indicates that those conditions occur relatively more frequently on the 100 km/h roads, while red that the conditions occur more frequently on 80 km/h roads. Data from the A9 highway with 80 km/h speed limit indicate higher frequencies of combinations with higher speeds and narrower acceleration ranges, suggesting less dynamic driving.

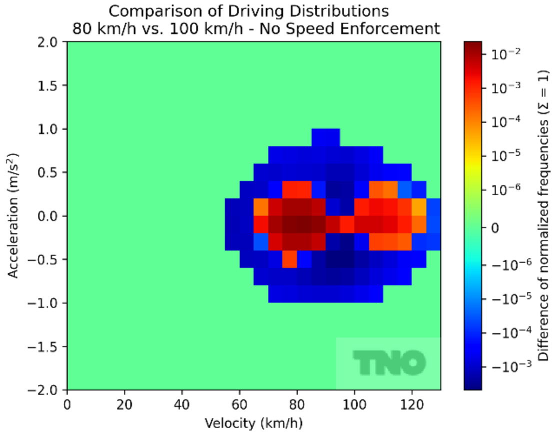


Figure C.8: Differences in normalized frequencies of acceleration and vehicle speed between roads with speed limits of 80 km/h and 100 km/h, under conditions of no enforcement. Dark red represents the most frequent occurrences. Data from the A9 highway with 80 km/h speed limit indicate higher frequencies of combinations with higher speeds and narrower acceleration ranges, suggesting less dynamic driving.

However, when compared with the definition of mild and aggressive acceleration at speeds above 80 km/h as considered in (Ligterink, 2016) the differences are very slight. The approach to emission factor determination in the absence of extensive monitoring for a certain road-type is to use a so-called driving vector (see Chapter 6 in (Ligterink, 2016)). Driving vectors quantify the proportion of time spent at various speeds and accelerations, normalized to 1 km of travel. Table C.2 details the time spent within different speed and acceleration ranges for both road types as driving vectors.

Table C.2: Driving vectors on roads with varying speed limits and enforcement conditions. The results from three different studies are compared: (Ligterink, 2016; Vroom *et al.*, 2023) and the current work. Note that 80 ZSH (2016) was based on expert judgement due to the lack of specific velocity data. The occupation of $q_9$ and $q_{10}$ fields are very similar for the 100 ZSH (2023) and 80 ZSH (2025) data.

| | | 80 ZSH (2016) | 100 ZSH (2016) | 100 ZSH (2023) | 80 ZSH (2025) |
|---|---|---|---|---|---|
| 1. Idling time | $q_1$ | 0 | 0 | 0.84 | 0.00 |
| 2. Time of velocities between 0-50 km/h | $q_2$ | 3.31 | 3.31 | 2.35 | 0.03 |
| 3. Normalized time of mild acceleration between 0-50 km/h | $q_3$ | 1.88 | 1.88 | 1.08 | 0.01 |
| 4. Normalized time of aggressive acceleration between 0-50 km/h | $q_4$ | 0.4 | 0.4 | 0.14 | 0.00 |
| 5. Time of velocities between 50-80 km/h | $q_5$ | 18.71 | 7.59 | 4.13 | 3.85 |
| 6. Normalized time of mild acceleration between 50-80 km/h | $q_6$ | 18.45 | 7.39 | 4.15 | 4.25 |
| 7. Normalized time of aggressive acceleration between 50-80 km/h | $q_7$ | 2.48 | 1.16 | 0.65 | 0.62 |
| 8. Time of velocities above 80 km/h | $q_8$ | 21.48 | 28.98 | 33.50 | 34.58 |
| 9. Normalized time of mild acceleration above 80 km/h | $q_9$ | 16.59 | 26.02 | 29.63 | 29.62 |

| | | 80 ZSH (2016) | 100 ZSH (2016) | 100 ZSH (2023) | 80 ZSH (2025) |
|---|---|---|---|---|---|
| 10. Normalized time of aggressive acceleration above 80 km/h | $q_{10}$ | 0.83 | 2.05 | 1.81 | 1.44 |

As mentioned earlier, there is low occupancy of $q_1$ – $q_8$ for 80 ZSH (2025) (i.e. speeds on the A9 remained generally above 80 km/h due to low traffic volume). The occupation of $q_9$ and $q_{10}$ fields are very similar for the 100 ZSH (2023) and 80 ZSH (2025) data. We do build on past expert judgement to conclude that the application of 80 ZSH to roads with higher traffic flows than the A9 would likely lead to $q_1$ – $q_8$ occupation more like 100 ZSH, which therefore reinforces the decision to set 80 ZSH equal to 100 ZSH.

Mobility & Built Environment

Anna van Buerenplein 1
2595 DA  Den Haag
www.tno.nl

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