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Including cold-start emissions in the Real-Driving Emissions (RDE) test procedure

An assessment of cold-start frequencies and emission effects

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Title: Including cold-start emissions in the Real-Driving Emissions (RDE) test procedure

Abstract
We document two independent analyses that were conducted to support the inclusion of cold-start emissions in the Real-Driving Emissions (RDE) test procedure. First, we present the results of a scoping review on cold-start frequencies and trip distances in Europe. Second, we present a scenario analysis that aims to quantify the impact of modifications in the RDE data pre-processing and evaluation on the calculated NO_X emissions over the urban part of an on-road test. We find that some 27 ± 5% of trips in Europe may contain a cold start. The driving distance between two consecutive cold starts reaches 36 ± 16 km (mean) and 30 ± 13 km (median), respectively. Our scenario analysis suggests that a simple inclusion of cold start into the regulatory RDE data evaluation procedure may not capture cold-start NO_X emissions in a robust manner. However, combining modifications of the RDE data pre-processing and the RDE data evaluation can capture at least part of the incremental cold-start NO_X emissions. A more systematic assessment of European driving data and an expansion of the scenario analysis presented here could substantiate the findings of this report.

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List of abbreviations, acronyms, and units

#	-	Number
%	-	Percent
BMVI	-	Bundesministerium für Verkehr und digitale Infrastruktur (Federal Ministry for Transport and Digital Infrastructure, Germany)
CADC	-	Common Artemis Driving Cycle
CBS	-	Statistics Netherlands (Centraal Bureau voor de Statistiek)
CSPI	-	Cold Start Performance Indicator [%]
d_{cold}	-	actual driving distance during cold start [km]
d_{urban}	-	reference driving distance, representing the typical distance driven by Europeans between two consecutive cold starts [km]
E_{CS}	-	average NO_X emissions during cold start [mg/km]
E_{Urban}	-	average NO_X emissions during urban driving with a warm engine [mg/km]
EC	-	European Commission
e.g.	-	*exempli gratia* (example given)
EU	-	European Union
GPS	-	Global Positioning System
GSM	-	Global System for Mobile Communications
h	-	hour
HBEFA	-	HAndbuch Emissions FAktoren (HAndBook Emission FActors)
i.e.	-	*id est* (that is)
JRC	-	Joint Research Centre
km	-	kilometre
M_{cold}	-	distance specific pollutant emissions during cold start [mg/km]
$M_{hot,urban}$	-	distance specific pollutant emissions during warm-engine operation as determined according to Appendices 5 or 6 of Regulation 2016/427 [mg/km]
M_{urban}	-	final distance-specific pollutant emissions over the urban part of a RDE trip [mg/km]
MAW	-	Moving Averaging Window
MAWP	-	Moving Averaging Window Performance [%]
mg	-	milligram
MS	-	EU Member States
NO_2	-	nitrogen dioxide
NO_X	-	nitrogen oxides

NO_XRDE_{Mod0a}	-	NO_X emissions calculated with the baseline scenario Mod0a [mg/km]
NO_XRDE_{Modi}	-	NO_X emissions calculated with the respective scenario *i*
PEMS	-	Portable Emissions Measurement System
PN	-	Particle Number
RDE	-	Real-Driving Emissions
s	-	second
SCR	-	Selective Catalytic Reduction
w	-	weighting factor for emissions from cold-start versus warm-engine operation
WLTC	-	Worldwide harmonized Light-duty vehicles Test Cycle
WLTP	-	Worldwide harmonized Light-duty vehicles Test Procedure

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Executive summary

The European Union implemented in 2016 the first two packages of the Real-Driving Emissions (RDE) test procedure as Regulations 2016/427 and 2016/646. The third regulatory RDE package addressing cold-start emissions, the testing of hybrid vehicles, and the measurement of particle number emissions was approved by a technical committee of experts from Member States in December 2016. During the stakeholder consultations on the third RDE package, several options for the inclusion of cold-start into the RDE test procedure were discussed. Member States supported a simple inclusion of the cold-start period into the normal RDE data evaluation. The Joint Research Centre, by contrast, proposed a separate calculation of distance-specific pollutant emissions for (i) the cold-start period and (ii) the warm-engine operation and a subsequent weighting of the resulting emissions by a factor that accounts for the distance typically driven by vehicle users between two consecutive cold starts.

The objective of this report is to document two independent analyses conducted by the JRC in support of the RDE stakeholder consultations on cold start. First, we conduct a scoping review of cold-start frequencies and trip distances in Europe. Second, we conduct a scenario analysis to investigate the effect of modifications in the RDE data pre-processing and evaluation procedures on the calculated NO_X emissions for urban driving. This analysis is based on actual on-road NO_X emissions data obtained from vehicle tests conducted at the JRC.

The reviewed driving data obtained from seven major sources suggest that some 27 ± 5% of trips are driven in Europe after vehicle parking of at least 3 to 8 h and may thus contain a cold start. Based on all collected data, the average driving distance between two consecutive cold starts reaches 36 ± 16 km (mean) and 30 ± 13 km (median), respectively. If only urban trips are considered, the distance between two consecutive cold starts reaches 25 ± 16 km (mean) and 27 ± 8 km (median), respectively. These findings are, in the strict sense, valid for the relatively conservative assumption that cold starts occur after a minimum parking duration of 3-8 h. Given the heterogeneity of temperature and driving conditions across the European continent, cold-starts may occur in real-word driving after longer/shorter parking durations, e.g., if the engines and after-treatment systems are thermally encapsulated/if vehicle operation occurs at ambient temperatures lower than 15°C.

The inclusion of cold start into the normal RDE data evaluation for 7 on-road trips yields both higher and lower overall urban NO_X emissions, although all tested vehicles show higher NO_X emissions during cold start than during warm-engine operation. This observation suggests that a simple inclusion of cold start into the normal RDE data evaluation may not capture cold start NO_X emissions in a robust manner. Modifications of (i) the data pre-processing (duplication of cold-start phase or change in the order of emission events) and (ii) the weighting of moving averaging windows (assuming a constant or linearly decreasing weighting factor for windows containing cold-start emissions) each increases on average the overall urban NO_X emissions but may also result for individual tests in decreasing NO_X emissions relative to the exclusion of cold start from the RDE evaluation. However, a combination of modifications in the RDE data pre-processing and evaluation might capture at least part of the incremental cold-start emissions.

We regard our findings as robust. Yet, a more systematic collection and assessment of driving data and an expansion of the scenario analysis covering more tests and vehicles could complement the findings presented here.

1 Introduction

The European Union (EU) has implemented in spring 2016 the first two packages of the Real-Driving Emissions (RDE) test procedure as Regulations 2016/427 and 2016/646 (EC, 2016a,b). RDE constitutes world-wide the first on-road test for the type approval of light-duty vehicles. In an initial monitoring phase, vehicles are tested on the road with so-called Portable Emissions Measurement Systems (PEMS) and their pollutant emissions have to be documented. From September 2017 onwards, binding not-to-exceed emission limits apply. In parallel to the implementation of the first two RDE packages, the European Commission has started working on two additional RDE package that address cold-start emissions, the testing of hybrid vehicles, the on-road measurement of particle number (PN) emissions, and the periodical regenerations of after-treatment systems (third RDE package) and administrative provisions for in-service conformity testing and market surveillance (fourth RDE package).

Cold start can contribute substantially to the overall vehicle emissions, specifically in urban areas, where trips are short, cold starts frequent, and air quality problems most severe (EEA, 2015). Moreover, nitrogen oxides (NO_x) emissions during cold start could become a major contributor to the overall NO_x emissions of diesel cars, once large parts of the diesel fleet are equipped with selective catalytic reduction (SCR) and lean NO_x-trap after-treatment systems. The European Commission (EC) therefore intends to implement dedicated cold-start provisions as part of the 3rd regulatory RDE package.

Several options for the inclusion of cold-start into the existing RDE Regulations 2016/427 and 2016/646 (EC, 2016a,b) have been discussed with Member States and other stakeholders since January 2016 in the RDE working group. Several Member States have supported a simple inclusion of cold-start into the normal RDE data evaluation. The Joint Research Centre (JRC), by contrast, had proposed a separate calculation of the distance-specific pollutant emissions for (i) the cold-start phase and (ii) the warm-engine operation and a subsequent weighting of the resulting emissions by means of a factor that accounts for the distance typically driven by vehicle users between two consecutive cold starts.

The objective of this report is to provide rationale for the discussions about the inclusion of cold start into the RDE test procedure. To this end, we present two separate analyses. First, we conduct a scoping review of available information on the typical trip distance and the frequency of cold starts in Europe. The results of this analysis could help defining a factor for the weighting of cold-start versus warm-engine emissions measured during the urban part of a RDE test. Second, we conduct a scenario analysis that investigates the effect of cold-start inclusions in and modifications of the RDE data evaluations on the calculated NO_X emissions. This analysis is based on selected vehicle tests and actual on-road NO_X emissions data. The results can help identifying elements in the data evaluation that could be amended to allow for a robust coverage of cold-start emissions by the RDE test procedure.

The report continues with additional background information (Section 2) and a short description of our research methods (Section 3). We present the results for the two independent analyses in Section 4. The report ends with a discussion and conclusions for policy makers in Section 5.

2 Background

Cold start in the context of RDE is defined by Regulation 2016/427 as the first 5 minutes after the initial start of the combustion engine[1]. If the engine coolant temperature can be reliably determined, the cold start period ends once the coolant has reached 343 K (70 °C) for the first time but no later than 5 minutes after initial engine start (EC, 2016a). Cold start emissions have to be recorded but are excluded from the emissions calculation until specific requirements are defined. At present, there are no requirements for the preconditioning of vehicles before an RDE test. However, the provisions of the recently approved third RDE package foresee that vehicles are driven for at least 30 min, parked with doors and bonnet closed and kept in engine-off status within moderate or extended altitude and temperatures for between 6[2] and 56 hours. The vehicle soak prior to RDE testing will be in line with the requirements for Type I testing in the laboratory that demands a minimum soak duration of 6 h. For the low-temperature Type IV test, the soak duration is set to 12 h (UNECE, 2015).

In January 2016, the European Commission has expressed the intention to cover cold-start emissions by the RDE test procedure; dedicated provisions for inclusion into the 3rd regulatory RDE package where then discussed throughout 2016 (EC, 2016c). The cold-start provisions contain three independent elements: (i) the preconditioning of vehicles including a precondition drive and vehicle soak, (ii) specific requirements for the driving conditions during cold-start and (ii) the evaluation of cold-start emissions.

First, to ensure cold-start is indeed part of RDE testing, the third regulatory RDE package foresees that vehicles will have to be preconditioned as described above at moderate or extended altitude (up to 700 and 1300 m, respectively) and temperatures (minimum temperature 0^{o}C and -7^{o}C, respectively[3]). Exposure to extreme atmospheric conditions (e.g., heavy snowfall, storm, hail) and excessive amounts of dust during the parking period should be avoided. If the vehicle was conditioned for the last three hours prior to the test at an average temperature that falls within the extended temperature, the pollutant emissions during cold start can be divided by a factor of 1.6, even if the running conditions are not within the extended temperature range.

Second, to ensure unbiased driving the 3rd regulatory RDE package requires for the cold-start period:

- an average vehicle speed (including stops) of 15-40 km/h;
- a maximum speed no more than 60 km/h;
- idling after the first ignition of the combustion engine not to exceed 30 s;

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[1] Regulation 2016/427 does not contain provisions for vehicle conditioning. However, the 3rd regulatory RDE package requires that vehicles are parked for at least 6 h before entering an RDE test. After such preconditioning, the temperature of the engine oil and coolant as well as of the emissions after-treatment technologies resembles that of the ambient air.

[2] Vehicle conditioning of 6 h might not in all cases ensure a complete engine cooldown, especially for larger engines or vehicles equipped with thermal engine encapsulation. Yet, a 6 h precondition period allows to precondition and test vehicles in one working day and could force the adoption of advanced thermal encapsulation that may yield real-world emission benefits.

[3] Until 5 years after effectiveness of Regulation 715/2009 (EC, 2007), moderate temperature conditions are limited to 3°C and extended temperature conditions to -2°C.

- total durations of all stops not to exceed 90 s, i.e., 30% of the cold-start duration as defined in Regulation 2016/427 (EC, 2016a).

Third, the evaluation of cold-start emissions had been subject to intensive discussions among RDE stakeholders. Two options were analysed in greater detail: (i) the inclusion of cold-start emissions into the normal RDE evaluation of the urban part of a trip as prescribed in Appendices 5 and 6 of Regulation 2016/427 (EC, 2016a) and (ii) a separate assessment of cold-start emissions and warm-engine emissions for the urban part of a trip followed by weighting of the two results.

Option 1 is simple and can easily be implemented into the existing regulatory RDE text but might not always assess cold-start emissions in a robust manner:

- The composition of a RDE trip is evaluated based on the realized vehicle speed, that is, Point 6 of Regulation 2016/427 and the RDE data evaluation defined in Appendices 5 and 6 of the same regulation use vehicle speed to classify events a urban, rural, or motorway driving. The speed-based classification leads to a situation where parts of the trip that are actually driven in a rural environment or on the motorway may be classified as urban driving if the instantaneous vehicle speeds or the average speed of moving averaging windows does not exceed 60 km/h and 45 km/h, respectively (EC, 2016a). Depending on route design and traffic conditions, RDE trips lasting some 90-120 min may thus cover longer urban distances than those typically driven by vehicle users between two consecutive cold starts. This observation is problematic as pollutant emissions during low-speed driving with fully warmed-up engine and after-treatment systems tend to be substantially lower than cold-start emissions.
- The data weighting applied in Appendices 5 and 6 of Regulation 2016/427 can lead to an under-representation of cold-start emissions. Appendix 5 weighs or excludes pollutant emissions if these belong to moving averaging windows those average CO_2 emissions deviate by more than 25% from the CO_2 reference curve (established by driving the vehicle on the chassis dynamometer with the WLTC). Appendix 6 categorizes three-second averages of pollutant emissions into power bins that are weighed based on a factor derived from a pre-defined frequency distribution, which gives relatively little weight to bins of high power. Related to the functioning of the data evaluation in Appendices 5 and 6, cold-start tests could be defeated by purposefully driving the cold start in an aggressive manner, which would lead to very high CO_2 emissions and the allocation of driving events into high power bins and, in turn, to a *de facto* exclusion of cold start emission from the evaluation of urban emissions.
- Pertinent to the moving averaging window method of Appendix 5, data points at the beginning and end of a test are contained in fewer averaging windows than data points in the middle of a test. When averaging the emissions of windows, cold start receives a disproportionately low weight in the overall data evaluation. Moreover, Regulation 2016/427 does not specify the order in which moving averaging windows have to be calculated. A window calculation starting from the end of a test entails the risk that cold-start data are not covered by any window.
- Pertinent to the power-binning method of Appendix 6 are challenges in evaluating hybrid vehicles; as the wheel power cannot be reliably estimated from the CO_2 emissions of such vehicles, the third regulatory RDE package specifies that Appendix 6 can only be applied to mild and full hybrid vehicles if the wheel power is measured, e.g., by a wheel torque sensor.

Taken together, we see a clear risk that the simple inclusion of cold start into the normal RDE data evaluation, without implementing complementary provisions, may (i) under-represent cold-start emissions compared to their actual contribution to real-world driving emissions and (ii) trigger biased driving during the cold-start period to simply defeat the RDE test. In view of these shortcomings, the JRC has proposed as Option 2 to separately assess cold-start emissions and the warm-engine emissions during urban driving and then apply a weighting factor for the calculation of the final emissions results as follows:

$$M_{urban}\left[\frac{mg}{km}\right] = w \cdot M_{cold}\left[\frac{mg}{km}\right] + (1-w) \cdot RDE_{hot,\,urban}\left[\frac{mg}{km}\right]$$

$$w = \frac{d_{cold}[km]}{d_{urban}[km]}$$

where:

M_{urban}	-	final distance-specific pollutant emissions over the urban part of a RDE trip [mg/km]
M_{cold}	-	distance specific pollutant emissions during cold start [mg/km]
$M_{hot,urban}$	-	distance specific pollutant emissions during warm-engine operation as determined according to Appendices 5 or 6 of Regulation 2016/427 [mg/km]
w	-	weighting factor
d_{cold}	-	actual driving distance during cold start
d_{urban}	-	reference driving distance, representing the typical distance driven between two consecutive cold starts in the EU

Option 2 would ensure that the weight of cold-start emissions in the final RDE result for urban driving that is comparable to the weight of cold start in the overall driving of European citizens. However, while Option 2 might capture cold-start emissions accurately, its implementation would add complexity to the RDE regulation and its effectiveness would hinge on the establishment of an appropriate weighting factor.

Several EU Member States have therefore expressed in the RDE meeting on 8 and 9 September 2016 their preference for Option 1, highlighting its simplicity and the observation that to date, no data had been presented that point to specific challenges related to cold-start emissions that are not yet covered by the existing Type 1 emissions tests.

If Option 1 is implemented in the 3rd regulatory RDE package, three areas for intervention could be considered, to make the evaluation of cold-start emissions more robust (Table 1):

- Ensuring the cold-start share in the total urban distance driven in a RDE trip matches the share of cold start in real-world driving. This objective could be achieved, e.g., by a map-based evaluation of the urban portion of a trip or by introducing a fixed distance after test start that should be considered for the evaluation of urban emissions.

- Adapting the pre-processing of data in Appendix 4 of Regulation 2016/427 (EC, 2016a) but leaving the actual evaluation of emissions data according to Appendices 5 and 6 unchanged. Options include (i) re-arranging of events in the recorded data stream, e.g., by cutting cold start from the beginning of a test and placing it into the middle of urban driving or (ii) the duplication of cold-start data, or (iii) the application of weighting factors to specific data segments.
- Adapting the data evaluation methods themselves, e.g., by applying a circular calculation of moving averaging windows to ensure events at the beginning and the end of urban driving are covered by a similar number of windows than events in the middle of the urban part of a trip.

Table 1: Principal options for adapting RDE provisions to ensure a robust coverage of cold-start emissions (according to Option 1, i.e., inclusion of cold start into the RDE data evaluation)

Adaptation	Options for implementation
Controlling for urban driving distance	- map-based evaluation of urban driving - implementation of a specific distance threshold, e.g., minimum RDE urban distance of 16 km or WLTC distance of 23 km to separate urban from rural driving
Pre-processing of data (Appendix 4)	- cutting the cold start section (i.e., first 300 s after engine start) and placing it into the middle of the data stream for urban driving, e.g., at a point when the first moving averaging window has been completed (≈10km) - duplicating the cold-start section and placing the duplicate, e.g., at the end of the test, at the end of urban driving - multiplying instantaneous cold-start emissions with a fixed or variable correction factor that accounts for the actual urban distance of a RDE trip
Adaptations of the data evaluation (Appendix 5)	- circular continuation of the determination of moving averaging windows to ensure data points at the beginning and end of urban driving are present in a similar number of windows than data points in the middle of urban driving - multiplying windows that contain cold-start emissions with a correction factor

Various combinations of the three adaptation types could be envisaged and any of these could be implemented into the RDE test procedure without complex adaptations of the existing regulatory text. However, depending on the choice, any of the suggested interventions could impact the severity of the RDE test procedure with respect to the importance of cold start relative to vehicle operation with a warm engine. Studying the emission effects might be straightforward in case of the first two adaptation types. However, studying the emissions effect of adapting the data evaluations in Appendix 5 of Regulation 2016/427 (EC, 2016a) might require somewhat more complex software reprogramming. In the following sections, we investigate in a preliminary scenario analysis the emission effects of a few selected adaptations of the RDE data pre-processing and the data evaluation with the moving averaging window method (see Sections 3.2 and 4.2).

3 Methods

3.1 Analysis of driving distance between two consecutive cold starts

In the first part of the analysis, we conduct a scoping review of information and statistical data on the length of trips and the frequency of cold starts with the objective to establish a first-order estimate of the distances typically driven by European vehicle users between two consecutive cold starts. Our analysis includes data from openly available scientific reports, peer-reviewed articles, technical presentations, and road vehicle emission models such as the Handbook of Emission Factors for Road Transport (HBEFA 3.2). This way, we identify seven sources of information that we present and discuss separately in Section 4.1.

Throughout this report, we define trips as driving events that are delimited by longer parking durations. Trips may contain multiple short trips, interrupted by stops at traffic lights or in congested traffic. The reviewed literature applies a variety of methodological choices to differentiate trips that contain a cold start from those that start with a warm engine or an engine that has not yet completely cooled down. The cool-down of engines and after-treatment systems (and their subsequent end-point temperature) generally depends on vehicle-specific design characteristics, on the driving pattern prior to vehicle parking and the ambient temperature. As a first, and relatively conservative proxy, we assume based on own assessments depicted in Figure 3 that after a parking duration of 3-8 h[4], engine and after-treatment systems have cooled down. Depending on the specific background information available from the various studies, we therefore assume that trips following a parking duration in the range of some 3-8 h contain a cold start. Throughout this report, we present error margins to indicate the standard deviation of values in a given data sample.

3.2 Scenario analysis - cold-start inclusions

In the second part of the analysis, we focus on modifications in the RDE data pre-processing according to Appendix 4 and in the actual data evaluation according to Appendix 5 of Regulation 2016/427 (EC, 2016a). This analysis excludes considerations on the actual urban driving distance covered by an RDE trip (see first bullet point on Page 3 and Table 1) because decisions on the respective driving distance that could be taken into account for the evaluation of urban emissions can be made independently of the applied data evaluation method, e.g., when designing an RDE trip. Instead, we seek to conduct a scenario analysis of the NO_X emissions effect of various modifications related to (i) the re-arrangement of emission events in the recorded data stream during pre-processing and (ii) modification of the weighting approach applied in Appendix 5 individual moving averaging windows. These modifications address the second and third bullet points on Page 3 as well as Columns 2 and 3 in Table 1 and should ensure cold-start emissions are sufficiently covered in individual windows and window containing cold-start emissions receive sufficient weight in the subsequent data evaluation.

[4] We acknowledge that this assumption represents a simplification; in reality, the cool-down characteristics of engines and after-treatment systems differ from each other and should ideally be dealt with separately.

As baseline scenario of our analysis, we assume the current RDE provisions (Regulations 2016/427 and 2016/646) that exclude cold start (i.e., pollutants emitted during the first 300 s of a trip) from the data evaluation. This scenario is referred to hereinafter as **Mod0a**.

We then establish four scenarios that assess modifications of the data pre-processing according to Appendix 4. These scenarios are aimed at increasing the number of averaging windows that contain cold-start emissions but leave the RDE data evaluation (i.e., the weighting of moving averaging windows according to Appendix 5) unchanged:

- Scenario **Mod0b** includes cold start into the normal RDE data evaluation according to Appendix 5 of Regulation 2016/427 but abstains from re-arranging emission events in the recorded data stream. This scenario is equivalent to the cold-start proposal of DG GROW for the third RDE package as of November 2016.
- Scenario **Mod1a** includes cold start into the RDE data evaluation and duplicates the cold-start segment in the recorded data stream. This scenario thus increases the number of windows that contain cold-start emissions compared to Scenario **Mod0b**.
- Scenario **Mod1b** includes cold start into the RDE data evaluation after cutting it from the beginning of the test and pasting into the middle of the urban part of the recorded data.
- Scenario **Mod1c** includes cold start into the RDE data evaluation after duplicating the cold-start segment (i.e., the first 300 s of a trip), cutting the duplicate from the beginning of the test and pasting it into the middle of the urban part of the recorded data. This scenario combines Scenarios **Mod1a** and **Mod1b** and would increase even further the number of windows that contain cold-start emissions compared to the baseline and previous two scenarios.

In a second stop of our scenario analysis, we assess two scenarios that modify the weighting approach of Appendix 5 to ensure sufficient weight is given to windows containing cold start. For these scenarios, we include cold start into the normal RDE data evaluation as done in scenario **Mod0b** but we do not re-arrange events in the recorded data stream:

- Scenario **Mod2a** applies a constant weighting factor of 1 to the first 300 moving averaging windows (i.e., the windows that do likely contain cold start emissions), irrespective of the actual CO_2 emissions of these windows. This scenario could prevent that the RDE data evaluation excludes cold-start windows with very high or low CO_2 emissions that may result from biased driving.
- Scenario **Mod2b** applies a linearly decreasing weighting factor from 2 to 1 for the first 300 MAWs. This scenario puts additional weight on the first windows of a trip that contain relatively large shares of cold-start emissions.

In a third step, we explore two selected combinations of scenarios that combine the pre-processing and the weighting of windows:

- Scenario **Mod3a** combines the duplication of cold start of scenario **Mod1c** with the application of a constant weighting factor of 1 for the first 300 MAWs in scenario **Mod2a**.
- Scenario **Mod3b** combines the duplication of cold start of scenario **Mod1c** with a linearly decreasing weighting factor from 2 to 1 applied to the first 300 moving averaging windows in scenario **Mod2b**.

We would like to emphasize that the scenarios are chosen to obtain a first and preliminary insight into the emissions effect of feasible and easily implementable modifications of the RDE data pre-processing and evaluation. The scenarios are chosen for a somewhat semiqualitative assessment of modifications but do not constitute a rigid evaluation of concrete proposals for the modification of the RDE data evaluation. Alternative, and equally relevant, modifications could be assessed in the future, e.g., a dedicated evaluation of emissions over the first moving averaging window of a trip or over a distance typically driven by vehicle users between two consecutive cold starts.

We demonstrate impact of the various scenarios on the calculated NO_X emissions by determining a cold start performance indicator (*CSPI*) [%] as:

$$CSPI = 100 \times \frac{E_{CS} - E_{Urban}}{E_{Urban}}$$

where:

E_{CS}	-	average NO_X emissions during cold start, i.e., the first 5 min of a RDE trip [mg/km] (as determined by applying the different scenarios)
E_{Urban}	-	average NO_X emissions during urban driving with a warm engine [mg/km]

The *CSPI* is calculated based on the instantaneous emissions data without the application of the RDE data evaluation methods; the *CSPI* can be expected to be high/low for vehicles with high/low cold start emissions compared to the average warm-engine emissions over the urban part of an RDE trip. The *CSPI* is a vehicle-specific, technology-specific, and trip-specific parameter.

We express the relative difference in the NO_X emissions between each modelled scenario and the baseline scenario **Mod0a** (cold start exclusion from RDE evaluation) as the moving averaging window performance (*MAWP*) [%] as:

$$MAWP = 100 \times \frac{NO_xRDE_{Modi} - NO_xRDE_{Mod0a}}{NO_xRDE_{Mod0a}}$$

where:

NO_XRDE_{Mod0a}	-	urban NO_X emissions calculated with the baseline scenario **Mod0a** [mg/km] (using the MAW method according to Regulation 427/2016)
NO_XRDE_{Modi}	-	urban NO_X emissions calculated with the respective scenario *i* [mg/km] (using the MAW method)

We analyse the NO_X emissions effect of the various scenarios based on seven on-road tests, conducted with four vehicles on four test routes (

Table 2). The selected tests were already conducted in 2013 and do not fully comply with the RDE requirements according to Regulations 2016/427 and 2016/646 (EC, 2016a,b). Still, we consider our selection to be fit for purpose as vehicles show higher NO_x emissions during cold start than during warm-engine operation for all tests.

Table 2: On-road tests used for the scenario analysis

Vehicle	Route	Test name
Gasoline Euro 6	#1	Test 1
Diesel Euro 6 #1	#1	Test 2
Diesel Euro 6 #1	#1	Test 3
Diesel Euro 6 #1	#1	Test 4
Diesel Euro 6 #2	#2	Test 5
Diesel Euro 6 #3	#3	Test 6
Diesel Euro 6 #3	#4	Test 7

4 Results

4.1 Driving distance between two consecutive cold starts

4.1.1 GPS car data: Driving patterns in Modena and Florence (Italy)

De Gennaro et al. (2014) and Paffumi et al. (2015) analysed trip characteristics based on a comprehensive set of GPS car data obtained for the Italian provinces of Modena and Florence. The data were acquired by on-board loggers whereby a GPS device (used to locate vehicles) sends data to a remote server via GSM (Global System for Mobile Communications). The data set comprises 28,000 vehicles, 4.5 million trips, and a total of 36 million vehicle-kilometres. The data were obtained over a one-month period in May 2011.

The analyses of De Gennaro et al. (2014) and Paffumi et al. (2015) suggest that the mean trip distance in the two provinces is 8 ± 3 km (mean trip distances are 7.8 km and 8.0 km in Modena and Florence, respectively). Approximately 20% of the parking events lasted 6 h or longer (Figures 1 and 2; Table 3). Applying the relatively conservative criterion[5] of 6 h or longer parking durations to distinguish trips that constitute cold starts from those being started with a warm or semi-warm engine, the data suggest that the mean distance between two consecutive cold starts (kilometres travelled per number of cold starts as analysed by Paffumi et al., 2015) is (8 ± 3) km/20% = **40 ± 15 km**.

This approximation is based on average trip distances and neglects that the probability distribution of parking durations and trip distances are positively skewed (non-symmetric). In fact, Figure 2 suggests that the median trip distance between two consecutive cold starts is somewhat shorter than the mean distance (i.e., in the range of some **30 km**).

[5] The longer the cut-off time, the more conservative the criterion. Applying a parking duration shorter that 6 h as criterion to distinguish between trips with and without cold start would increase the percentage of trips containing a cold start. At an ambient temperature of 15°C, the engine coolant temperature may have approximately reached the ambient temperature (see Figure 3). We acknowledge that the level of pollutant emissions depends on the temperature of the after-treatment systems (but not directly on the temperature of the engine). As the catalyst likely cools down faster than the engine coolant does, parking durations shorter than 6 h could be assumed to differentiate trips with and without cold start from each other.

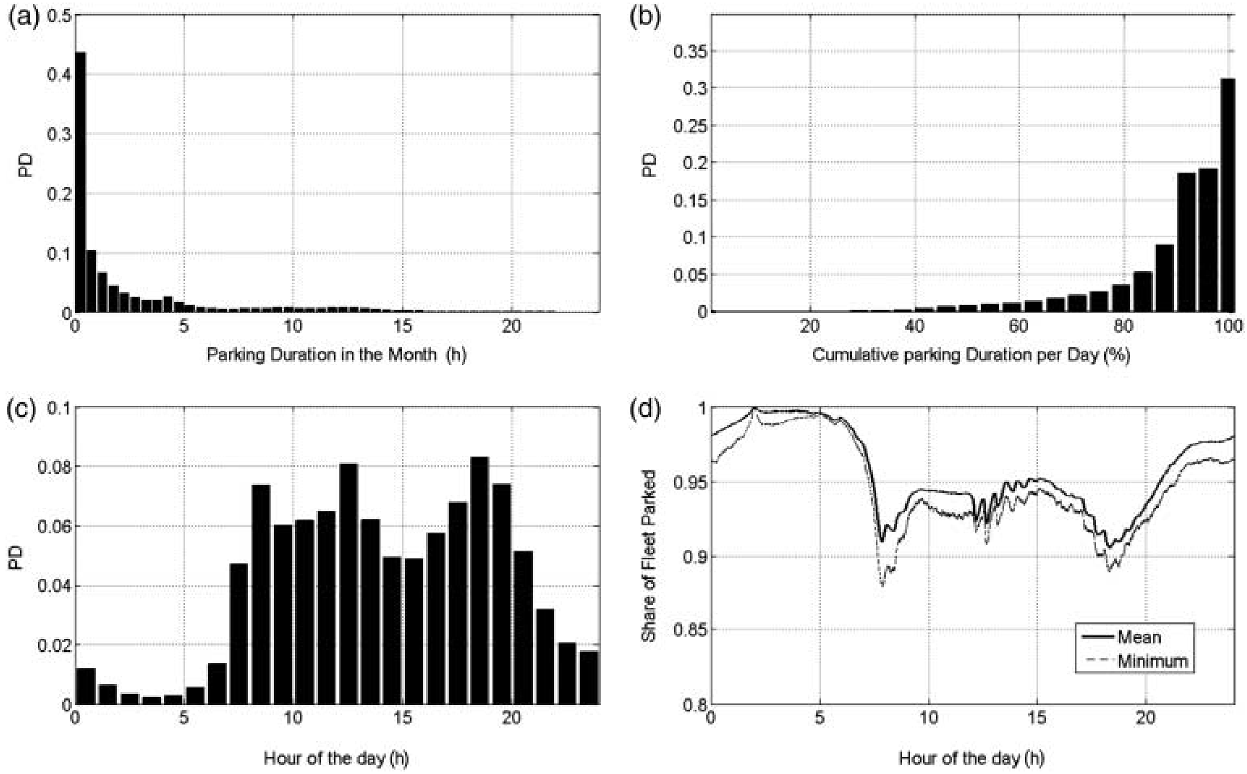

Figure 1: *Province of Modena (Italy), second-by-second calculations: (a) Frequency distribution of parking durations in hours (0.5 h bin size); (b) Cumulative parking duration per day; (c) Rate of parking during the day (hours); (d) Share of the fleet sample parked during the day (Source: Paffumi et al., 2015)*

After the parking of a vehicle, the cooling of engine and after-treatment systems typically follows an exponential trend with temperatures decreasing at a declining rate over time, eventually approaching the ambient temperature asymptotically. Figure 3 shows that at an ambient temperature of 15°C, the engine coolant temperature (a proxy for the temperature of the engine and after-treatment systems) might have fallen to below 30°C after a parking duration of 3 h[6], which appears to represent some 30% of all parking events in Modena (De Gennaro et al. (2014); Table 3). Applying the more stringent 3 h criterion to distinguish between trips with and without cold start yields an average distance travelled between two consecutive cold starts of (8 ± 3) km/30% = **27 ± 8 km** and a median distance between two consecutive cold starts of 30 km*20%/30% **= 20 km**.

[6] Again, we acknowledge that the level of pollutant emissions depends on the temperature of the after-treatment systems, which likely cools down faster than the engine coolant does. Moreover, the cooling of the engine depends on the individual vehicle. Figure 3 therefore constitutes a schematic sketch that could be complemented by more detailed and vehicle-specific analyses.

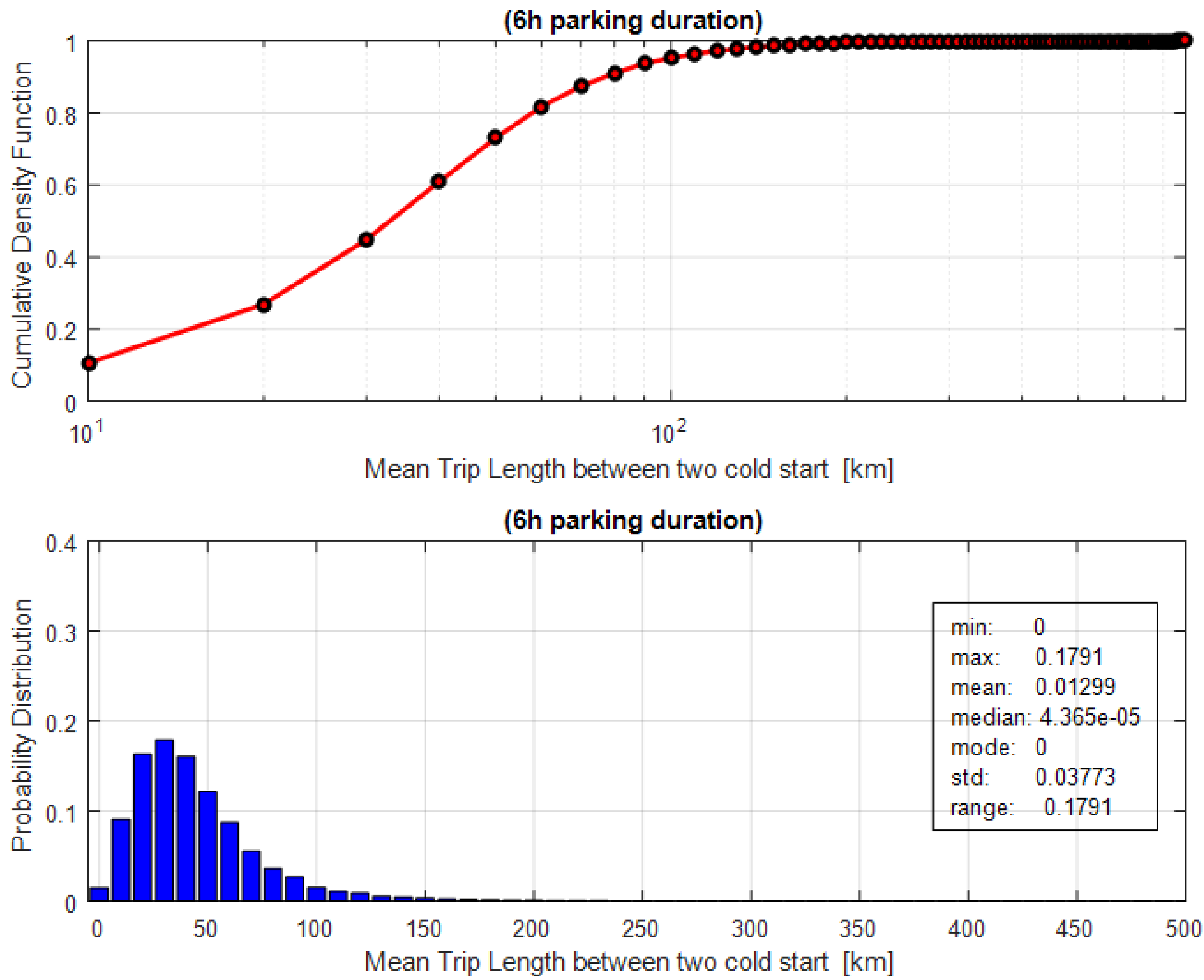

Figure 2: *Frequency distribution of trip lengths, i.e., driving distance between two consecutive cold starts after a parking duration of at least 6 h (Source: Paffumi et al., 2015)*

Table 3: *Distribution of parking durations in the province of Modena (Italy; Source: De Gennaro et al., 2014)*

Parking duration in h	Percentage	Cumulative percentage
0-0.5	43.5	43.5
0.5-1	10.4	53.9
1-1.5	6.6	60.5
1.5-2	4.5	65.0
2-2.5	3.2	68.2
2.5-3	2.5	70.7
3-6	10.5	81.2
6-12	9.3	90.5
12-24	7.5	98.0
>24	2.0	100

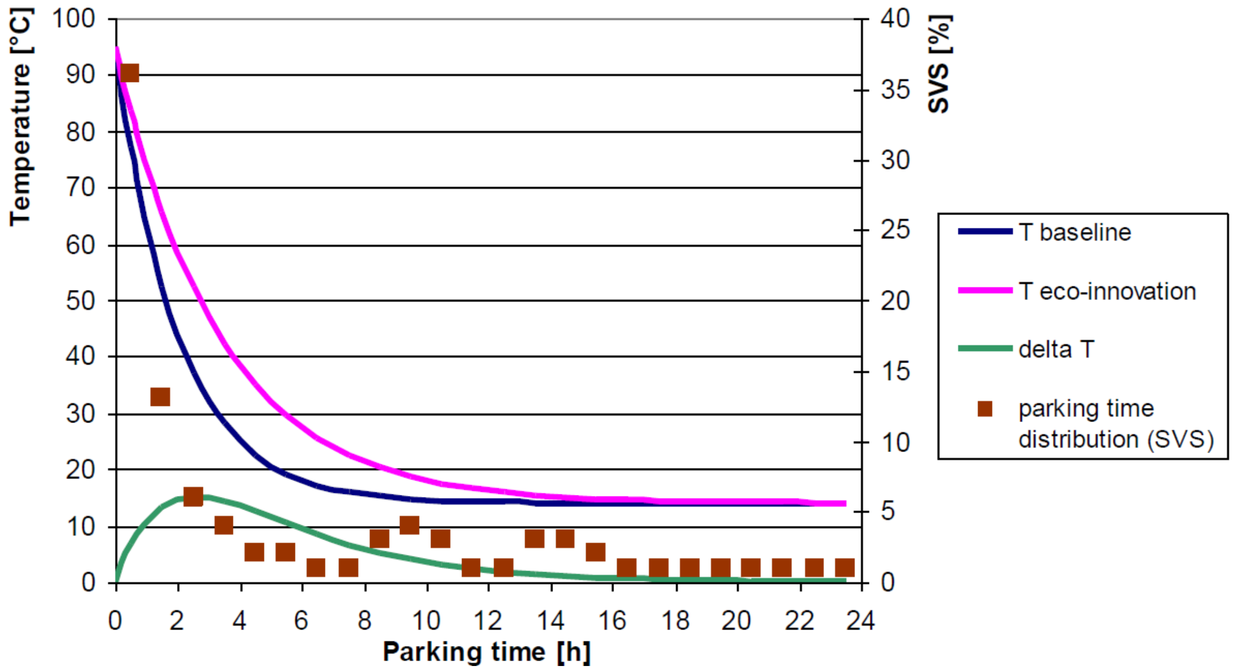

Figure 3: Generic cool-down curve for engine coolant (Source: EC, 2015)

4.1.2 Green eMotion data

Donati et al. (2015) complemented the driving data analysed by De Gennaro et al. (2014) and Paffumi et al. (2015) with those from hybrid and electric vehicles that participated in the Green eMotion project. The Green eMotion data contain information about the driving patterns of hybrid and electric cars, motorcycles, and transporters recorded by on-board data loggers in the period between March 2011 and December 2013. The vehicles were driven in 11 demonstration regions, in various cities of six European countries (Denmark, France, Germany, Ireland, Italy and Sweden). The data set comprises 457 vehicles and a total of 65,799 trips. The mean and median trip distances travelled are 7.8 km and 4.8 km, respectively (Figure 4). Donati et al. (2015) argue that the mean trip distance is negligibly shorter than the one identified by De Gennaro et al. (2014) and Paffumi et al. (2015; see Section 4.1.1) because the Green eMotion vehicles were mainly propelled electrically and thus tend to be driven predominantly within cities. This observation may make the driving data obtained by Donati et al. (2015) specifically appropriate for characterizing the EU-wide driving pattern in urban environments.

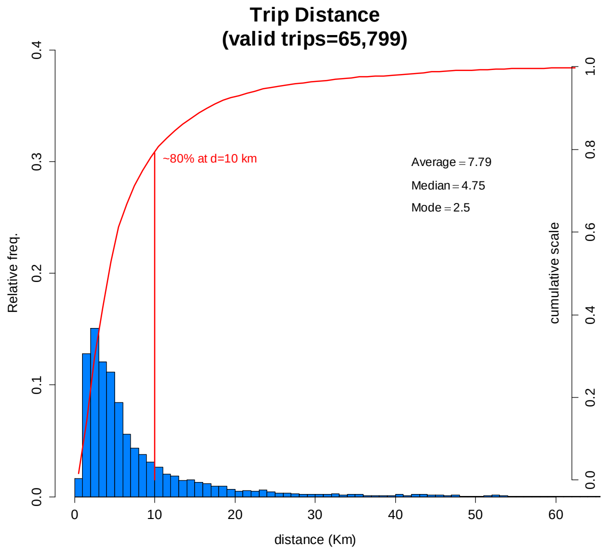

Figure 4: Distribution of trip distances as obtained from the Green eMotion data; bars (blue) denote the relative frequency of trip distances; the red line denotes the cumulative frequency distribution of trip distances (Source: Donati et al., 2015)

As the distribution of trip distances, also the distribution of parking times is skewed towards shorter parking durations (Figure 5). Parking times reach on average 3.3 h with some 27% and 20% of parking events being longer than 3 h and 6 h, respectively. These observations are well in line with the findings of De Gennaro et al. (2014) and Paffumi et al. (2015). If we apply the 27% and 20% criteria to distinguish trips with and without cold starts, we obtain the following driving distances between two consecutive cold starts:

- Mean distance between two consecutive cold starts (≥3 h parking): 7.8 km/27% = **29 km**.
- Mean distance between two consecutive cold starts (≥6 h parking): 7.8 km/20% = **39 km**.
- Median distance between two consecutive cold starts (≥3 h parking): 4.8 km/27% = **18 km**.
- Median distance between two consecutive cold starts (≥6 h parking): 4.8 km/20% = **24 km**.

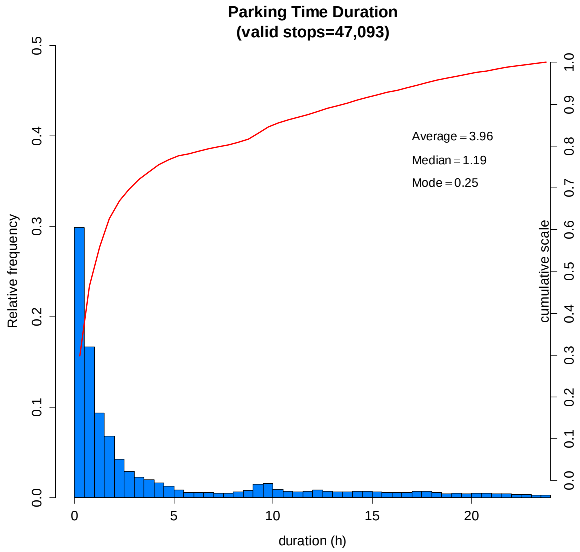

Figure 5: Distribution of parking times as obtained from the Green eMotion data; bars (blue) denote the relative frequency of parking times; the red line denotes the cumulative frequency distribution of parking times (Source: Donati et al., 2015)

4.1.3 Driving data from the Netherlands

Klein et al. (2015) presented data on the trip distance and frequency of cold starts in a mobility study conducted already in 1995 by Statistics Netherlands (CBS). The study consists of interviews of a large, random group of car owners about the use of their vehicle on particular days. According to Klein et al. (2015), the average distance of trips in the Netherlands is 14.5 km[7]. Approximately 60% of trips are assumed to contain a cold start[8]; the total number of cold starts per travelled kilometre is therefore 0.04 (i.e., a cold start happens on average every **24 km**). Approximately 95% of all cold starts take place within urban areas. In 1995, according to Statistics Netherlands, 25% of the passenger vehicle kilometres were driven within urban areas and about 35% on rural roads; the number of cold starts per passenger car kilometre on urban roads is approximately 0.15 (i.e., a cold start happens on average every **6.7 km**) but, due to longer trip distances, on rural roads only 0.05[9] (i.e., a cold start happens every **20 km**).

We note that the cold-start frequency of 60% as identified by Klein et al. (2015) differs considerably from the 20-30% presented in Sections 4.1.1 and 4.1.2. Moreover, the mean travelled distance of 14.5 km identified by Klein et al. (2015) is almost double that of 8 km and identified by De Gennaro et al. (2014), Paffumi et al. (2015), and Donati et al. (2015). A possible explanation is that these authors considered predominantly urban driving, and that the Green eMotion data consider urban trips of electric vehicles. The deviations in the

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[7] More recent data for the year 2015 suggests that Dutch drivers make on average 0.85 car trips per day, thereby covering a distance of 18 km (Ligterink (2016) based on CBS (2016)).

[8] Klein et al. (2015) refer to cold start as driving with a cold engine (presumably at ambient temperature) without, however, specifying after which parking duration the conditions for a cold-start are satisfied.

[9] Klein et al. (2015) specify the number of cold starts per passenger car kilometre for rural roads to be approximately 0.005. Personal communication with Ligterink (2016) suggests the actual number of cold starts is in fact a factor ten lower, i.e., 0.05.

frequency of cold starts is most likely caused by different assumptions regarding the minimum parking time after which the engine has cooled down and a new trip begins with a cold start. According to Table 3, 60% of parking times in Modena (Italy) are within a duration of 0.5 h; this time interval is relatively short to allow for engine cool-down (see also Figure 3). In fact, Klein et al. (2015) do not specify the duration of parking time used to determine whether a vehicle start is a cold start. Moreover, whereas the GPS car data (De Gennaro et al., 2014; Paffumi et al., 2015) and Green eMotion data (Donati et al., 2015) are based on measured trip distances and durations, the data Klein et al. (2015) analysed are based on surveys. Ligterink (2016) argues that the data presented by Klein et al. (2015) might be more representative of the average car use than GPS data as the former also include older cars. In the Netherlands, cars of 8 years and older typically drive less than 10,000 km per year and are predominantly used for urban driving.

4.1.4 Driving data from Sweden

Karlsson (2013) logged the movements of 432 passenger cars in private use with a GPS for a research project on car movements in Sweden. The cars had an age of 0-100 months since registration and were driven in Västra Götaland county (including Gothenburg, the second-largest city in Sweden) and the Kungsbacka municipality. The cars were randomly selected from the Swedish vehicle register; loggings were distributed over the seasons in the period between 2010 and 2012. Karlsson (2013) considers the car sample to be approximately representative of Sweden in terms of movement patterns, car ownership, and the coverage of larger and smaller towns and rural areas. The movements of each car were logged for 1-3 months (58 days on average).

Karlsson (2013) find that the majority of trips are shorter than 5 km (Figure 6) and some 25% of parking events last for 6 h or longer (Figures 7). Meta data provided by Karlsson and Björnsson (2016) through personal communication suggest that cars were driven on average **47 ± 25 km** (mean) and **42 km** (median)[10] between parking events that lasted 6 h or longer.

[10] This median represents the median of the mean driving distances covered by each individual car between parking durations of 6 h or longer.

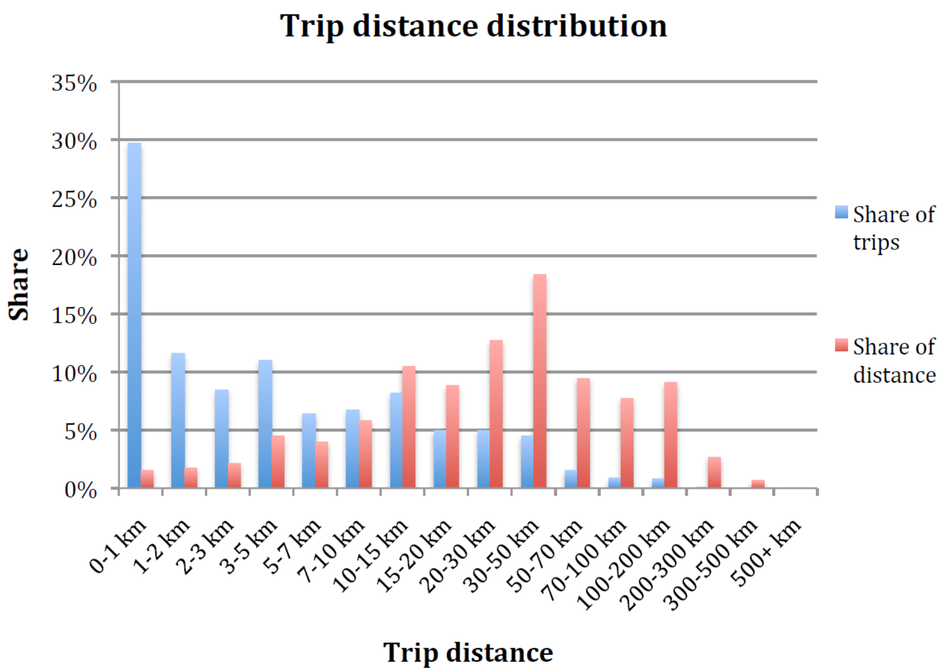

Figure 6: Frequency distribution of trip distances in Sweden (Source: Karlsson, 2013)

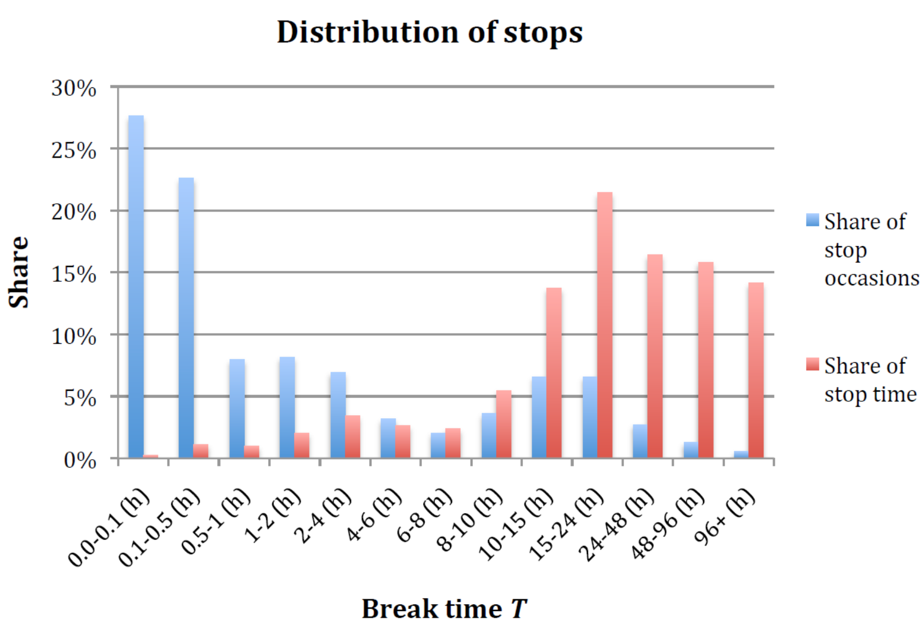

Figure 7: Frequency distribution of parking durations (referred to here as break time T) in Sweden (Source: Karlsson, 2013)

4.1.5 WLTP data base and miscellaneous data sources

An analysis of 430,000 km and 35,850 trips of European driving data contained in the entire data base of trips used for the development of the Worldwide harmonized Light Vehicles Test Procedure (WLTP) suggests a mean trip length of 10.5 km (Steven, 2016). Donati et al. (2015) also found a mean of 9.8 km (Modena) and 10.3 (Florence) in their re-analyses of all the floating-car data, i.e., not restricting their analysis to urban driving. Assuming an mean trip distance of 10.5 km and a cold-start frequency of 27% (≥3 h parking) and 20% (≥6 h parking), yields mean distances between two consecutive cold starts of **39 km** and **53 km**, respectively.

A back-of-the-envelope calculation proposed by ACEA (2016) suggested an average annual mileage per car of ≥14,000 km, some ≤2 cold-starts per day (i.e., ≤720 cold starts per year), and thus an average distance between two consecutive cold starts of **≥19.4 km**.

In preparation of the work on the 3rd RDE package, the JRC had compiled a preliminary review of European trip distances (Table 2). The results are in line with the other findings presented in Section 4.1.1, suggesting the mean and median distance of trips (including urban and extra-urban driving) in Europe reach 14 ± 5 km and 12 km, respectively. As observed previously, the distribution of trip distances is positively skewed, with the majority of trips being shorter than the mean.

If we assume that 27% and 20% of trips begin with a cold start (De Gennaro et al., 2014; Paffumi et al., 2015), we obtain the following driving distances between two consecutive cold starts:

- Mean distance between two consecutive cold starts (≥3 h parking): 14 ± 5 km/27% = **52 ± 19 km**.
- Mean distance between two consecutive cold starts (≥6 h parking): 14 ± 5 km/20% = **70 ± 25 km**.
- Median distance between two consecutive cold starts (≥3 h parking): 12 km/27% = **44 km**.
- Median distance between two consecutive cold starts (≥6 h parking): 12 km/20% = **60 km**.

Table 4: Preliminary review of European trip distances based on miscellaneous sources (not all trips driven in one day may include a cold start; primary sources of information not included in the list of references)

Source	Year	Country	Trips per day	Distance per trip [km]	Comment
Pasaoglu et al. (2012)	2012	France	2.9	19 commuting; 15 free time[1]	Based on a web survey of 600 participants in 6 EU Member States
		Germany	2.6	25 commuting; 15 free time[1]	
		Italy	2.7	17 commuting; 16 free time[1]	
		Spain	2.4	25 commuting; 34 free time[1]	
		Poland	2.5	24 commuting; 20 free time[1]	
		United Kingdom	2.5	18 commuting; 15 free time[1]	
ISFORT (Mobility in Italian cities)	2008	Italy	3.12 (average of mobility in big cities)	12 (average of mobility in big cities)	15,000 interviews per year, age between 14-80, working days
Città metropolitane: Mobilità, crisi e cambio modale	2015	Italy	2.7 (average of mobility in big cities)	11.5 (average of mobility in big cities)	15000 interviews per year, age between 14-80, working days
XX Rapporto Aci-CENSIS	2012	Italy	3 on week days; 2.1 on weekends	10 on weekdays; 11 on weekends	Average of various cities
National Travel Survey: 2013	2013	United Kingdom	2.5	11.5	Survey based on about 9000 households
Mobilität in Deutschland 2008	2008	Germany	3.5	11.8	Survey based on 25000 households
Eurostat: Passenger mobility in Europe	1999-2001	Denmark	2.7	12.7	Data collected between1999-2001; data collected based on populations of up to 40,000 households depending on the studied country
		Germany	3.4	11.7	
		France	2.9	12.2	
		Latvia	1.9	4.6	
		The Netherlands	3.3	10.2	
		Austria	3	9.4	
		Finland	2.9	15.4	
		Sweden	2.7	16.3	
		United Kingdom	2.9	11	
		Switzerland	3.6	13	
		Norway	3.3	11.5	
Traffic patterns	2010	Switzerland	2.7	13.6	Survey based on 63000 individuals
National travel survey	2009	Ireland	2.4	13	Survey based on 7000 households
Car ownership, travel and land use: a comparison of the US and Great Britain	2006	United Kingdom	3	8.7	
Mean			2.8	13.8	
Standard deviation			0.4	4.9	
Median			2.7	12.2	

[1]For the calculation of the overall mean, standard deviation, and median, we assume commuting occurs on 5 out of 7 days of the week and driving in free time on 2 out of 7 days of the week.

An analysis conducted by the European Federation for Transport and Environment (T&E 2016a,b) based on a collection of data from national travel surveys of various European countries (Belgium, France, Germany, Italy, UK) and complemented with data for Latvia and Sweden suggests that roughly 50% of car trips in urban environments are shorter than 6 km (Figure 8). This observation is consistent with the findings of Karlsson (2013) and Donati et al. (2015). Assuming that 27% and 20% of trips begin with a cold start (De Gennaro et al., 2014; Paffumi et al., 2015), we obtain the following median driving distances between two consecutive cold starts:

- Median distance between two consecutive cold starts (≥3 h parking):
  6 km/27% = **22 km**.
- Median distance between two consecutive cold starts (≥6 h parking):
  6 km/20% = **30 km**.

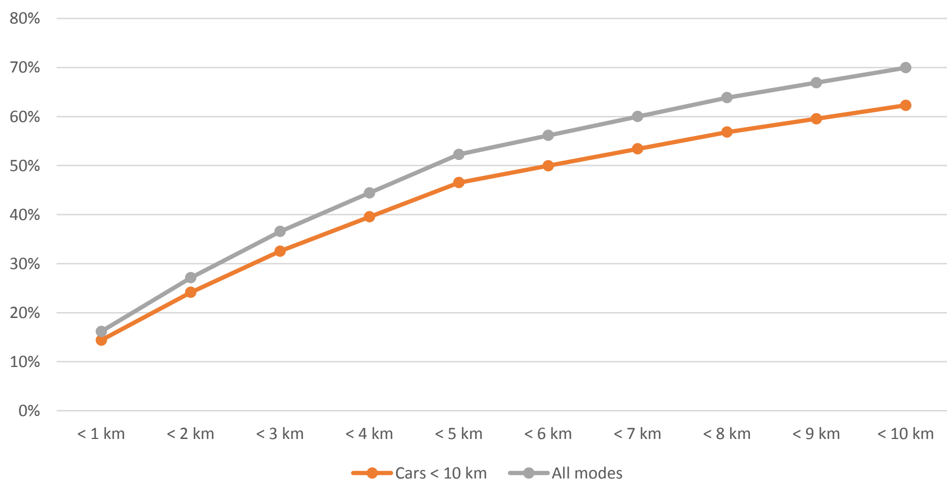

Figure 8: Distribution of urban trip distances in the EU based on miscellaneous data sources (Source: T&E, 2016a,b)

4.1.6 Handbook Emission Factors for Road Transport (HBEFA 3.2)

The data contained in HBEFA (version 3.2) suggest the overall mean and median distance of trips in six European countries reach 8.3 ± 1.6 km and 4.9 km, respectively (Table 5). The positively skewed distribution of trip distances results in a relatively low median with the majority of trips being shorter than the mean. The distribution of parking times in HBEFA 3.2 suggests that on average over all countries covered, 31 ± 7 % (mean) and 35% (median) of all trips are started under cold conditions, i.e., after a parking time of more than 8 h (Kühlwein, 2016; Table 6). By contrast, hot start after a stand-still time of less than 1 h accounts for some 37 ± 9% (mean) and 35% (median) of all trips. The remaining trips are started under warm conditions after parking times between 1 h and 8 h (Kühlwein, 2016).

Table 5: Frequency distribution of trip distances in 6 European countries (Source: Kühlwein (2016) based on HBEFA 3.2); primary sources of information not included in the list of references

Distance class	Country	Germany	Austria	Switzerland	France	Norway	Sweden
	Data source	Not specified	Not specified	Not specified	Lille, 1998	Statistics Norway	from instrumented cars, VTI
	Average distance per class [km]	Frequency [%]					
0-1 Km	0.50	10.30	10.00	7.00	11.50	15.45	23.77
1-2 Km	1.50	13.40	13.00	9.00	20.50	13.39	7.43
2-3 Km	2.50	10.90	11.00	12.50	14.00	9.64	7.92
3-4 Km	3.50	7.05	7.00	5.00	10.00	6.30	9.90
4-5 Km	4.50	7.05	7.00	8.00	8.00	7.65	7.92
5-6 Km	5.50	6.05	6.00	9.50	6.00	4.67	3.96
6-7 Km	6.50	6.05	6.00	6.50	4.00	3.40	2.48
7-8 Km	7.50	3.03	3.00	4.50	3.50	3.66	8.91
8-9 Km	8.50	3.03	3.00	3.50	2.50	1.06	5.94
9-10 Km	9.50	3.03	3.00	3.00	2.50	6.52	2.97
10-11 Km	10.50	2.06	2.00	3.50	2.00	0.62	1.39
11-12 Km	11.50	2.06	2.00	3.00	2.00	1.73	1.39
12-13 Km	12.50	2.06	2.00	2.00	2.00	0.79	1.39
13-14 Km	13.50	2.06	2.00	1.50	2.00	0.56	1.39
14-15 Km	14.50	2.06	2.00	1.50	1.00	3.93	1.39
15-16 Km	15.50	0.96	1.00	2.00	1.00	0.64	0.52
16-17 Km	16.50	0.96	1.00	1.00	1.00	0.57	0.52
17-18 Km	17.50	0.96	1.00	1.50	1.00	0.57	0.52
18-19 Km	18.50	0.96	1.00	1.00	1.00	0.16	0.52
19-20 Km	19.50	0.96	1.00	1.00	1.00	4.08	0.52
>20 Km	30.00	15.00	16.00	13.50	3.50	14.60	9.24
Distance of all trips							
Mean [km]	8.3 ± 1.6[1] (all countries)	9.2 km	9.5 km	9.4 km	5.8 km	9.1 km	7.1 km
Median [km]	4.9 (all countries)	5.2 km	5.3 km	5.9 km	3.7 km	5.1 km	4.2 km

[1] Uncertainty margin corresponds to the standard deviation of mean trip distances for all countries.

This observation has two implications. First, when applying the criterion of 8 h parking time, the average distance between two consecutive cold starts may range between 8.3 ± 1.6 km/31 ± 7% = **27 ± 8 km** (mean distance/mean share cold-start trips) and 4.9 km/35% = **14 km** (median distance/median share cold-start trips)[11]. Second, starting conditions in which the engine is not completely cooled down or warmed up constitute indeed a substantial part of real-world driving. To account for such intermediate conditions at the beginning of a trip, HBEFA includes specific emission factor functions for each pollutant and vehicle concept (Kühlwein, 2016).

[11] The distances calculated here represent conservative estimates. Considering that after-treatment systems cool down faster than the engine coolant does, one could assume shorter parking durations, which in turn yields shorter distances between two cold starts. More detailed scenario analyses could complement the analysis presented here.

Table 6: Frequency distribution of parking time in 6 European countries (Source: Kühlwein (2016) based on HBEFA 3.2); primary sources of information not included in the list of references; EI-TG – Eco-Innovations Technical Guidelines (EC, 2015)

Country	Germany	Germany	Austria	Switzerland		France	Norway	Sweden	
Data source	DRIVE, 1991	SRV, 1994	DRIVE, 1991	MZ05	MZ10	Lille, 1998	Statistics Norway	from instrumented cars, VTI	EI-TG
Time class [min]	Frequency [%]								
<30	14.14	21.79	14.14	20.21	17.07		22.00	42.79	
30-60	27.46	12.41	27.46	10.02	10.41	36.00	8.30	13.93	36.00
60-90	3.60	6.79	3.60	6.52	7.06		5.10	1.99	
90-120	7.00	6.79	7.00	5.26	4.63	9.00	5.80	4.98	13.00
120-150	2.21	2.98	2.21	3.69	3.63		3.20	5.97	
150-180	4.29	2.98	4.29	3.31	2.98	6.00	3.60	1.99	6.00
180-210	1.43	1.78	1.43	2.51	2.57		2.20	2.99	
210-240	2.77	1.78	2.77	2.69	2.72	9.00	2.60	1.49	4.00
240-270	0.83	0.88	0.83	2.86	2.56		1.50	1.49	
270-300	1.62	0.88	1.62	2.31	2.40	7.00	1.60	1.00	2.00
300-330	0.83	0.74	0.83	1.56	1.68		1.00	1.00	
330-360	1.62	0.74	1.62	0.98	1.30	3.00	1.10	0.50	2.00
360-390	0.48	0.77	0.48	0.75	0.83		0.80	1.00	
390-420	0.92	0.77	0.92	0.71	0.67	6.00	1.40	0.50	1.00
420-450	0.48	0.51	0.48	0.61	0.67		1.80	0.50	
450-480	0.92	0.51	0.92	0.63	0.83	24.00	2.40	0.50	1.00
480-510	29.40	0.91	29.40	0.85	0.94		2.10	0.50	
510-540		1.19		1.08	1.23		2.00	0.50	3.00
540-570		1.45		1.36	1.49		1.00	0.50	
570-600		1.80		1.48	1.86		0.90	0.50	4.00
600-630		1.72		1.36	1.78		0.90	0.50	
630-660		1.42		1.34	1.47		0.90	0.50	3.00
660-690		1.30		1.13	1.34		0.80	0.50	
690-720		1.36		1.27	1.40		26.90	13.88	1.00
>72		25.73		25.54	26.53				24.00
COLD ≥8h	29	37	29	35	38	24	36	17	35
HOT ≤1h	42	34	42	30	27	36	30	57	36
Warm >1 to<8 h	29	29	29	34	35	40	34	26	29

4.1.7 CADC and related trip analyses

The research of André et al. (1999) in support of establishing the Common Artemis Driving Cycle (CADC) suggests that 69% of trips start with a cold or not fully warmed up engine (Table 7). This observation is in line with the data of HBEFA 3.2 (Kühlwein, 2016) and the findings of De Gennaro et al. (2014), Paffumi et al. (2015), and Donati et al. (2015). The trip distance driven after a cold start reaches some 9.1 km (Table 8). However, this distance only considers the trip following a cold start and does not consider any driving distance potentially covered by subsequent trips that start with a warm or partially cooled-down engine. We would thus argue that the driving distance between two consecutive cold starts is thus longer than the 9.1 km obtained from André et al. (1999).

Table 7: *Percentage of driving distance covered by trips that start with a cold or partially warmed up engine (Source: André et al. (1999) cited from André and Joumard, 2005)*

Average trip speed [km/h]	Winter (4 months)	Summer (4 months)	Intermediate season (4 months)	Full year
	Percentage of total driving distance			
<10	61.7	62.7	58.9	61.3
10 to 20	71.9	71.1	56.9	67.7
>20 to 30	71.8	67.1	62.8	67.7
>30 to 40	78.8	68.6	64.8	72.2
>40 to 50	80.9	76.3	66.5	75.6
>50 to 60	77.0	76.7	60.6	71.7
>60 to 70	74.6	67.9	76.6	72.9
>70	67.3	58.9	57.6	62.9
Total	73.4	67.3	63.2	69.0

Table 8: *Distance of trips containing cold start (Source: André et al. (1999) cited from André and Joumard, 2005)*

Distance class [km]	Average distance [km]	Speed category [km/h]						Total
		<10	10 to 20	>20 to 30	>30 to 40	>40 to 50	>50	
		Average speed to reach warm-engine conditions [km/h]						
		5.4	15.3	24.9	34.6	44.3	60.9	
		Distance [km/h]						
<0.5	0.2	0.3	0.1	0.0	0.0	0.0	0.0	0.1
0.5 to 1	0.8	0.6	0.5	0.2	0.0	0.0	0.0	0.2
>1 to 2	1.5	2.2	2.4	1.7	0.6	0.1	0.0	1.2
>2 to 3	2.5	3.0	4.3	3.9	1.3	0.5	0.0	2.5
>3 to 4	3.4	2.2	3.0	3.2	2.6	1.2	0.2	2.3
>4 to 5	4.5	3.2	4.7	4.7	2.9	1.6	0.7	3.3
>5 to 6	5.5	3.9	5.6	4.9	3.9	1.8	1.2	2.9
>6 to 7	6.5	3.9	4.9	4.2	4.0	1.9	0.8	3.5
>7 to 8	7.4	2.3	3.3	3.4	2.4	3.4	0.7	2.8
>8 to 9	8.5	1.9	2.1	2.3	2.6	1.1	0.7	1.9
>9 to 10	9.5	1.0	1.7	3.1	4.3	2.1	1.3	2.5
>10 to 11	10.5	1.2	3.7	2.4	4.6	3.6	0.9	3.0
>11 to 12	11.5	2.2	2.4	2.8	4.0	1.5	0.9	2.5
>12	34.6	71.9	61.3	63.1	66.8	81.4	92.5	70.3
Total	9.1	100.0	100.0	100.0	100.0	100.0	100.0	100.0

4.2 Scenario analysis – cold-start inclusion

4.2.1 Baseline scenario and simple RDE cold-start inclusion

We start out by characterizing the NO_X emissions of the selected tests. Figure 9 presents the RDE results over the urban part of trips for the baseline scenario **Mod0a** (exclusion of cold start from the RDE data evaluation in accordance with Regulation (EU) 2016/427) and scenario **Mod0b** (inclusion of cold start into the RDE data evaluation).

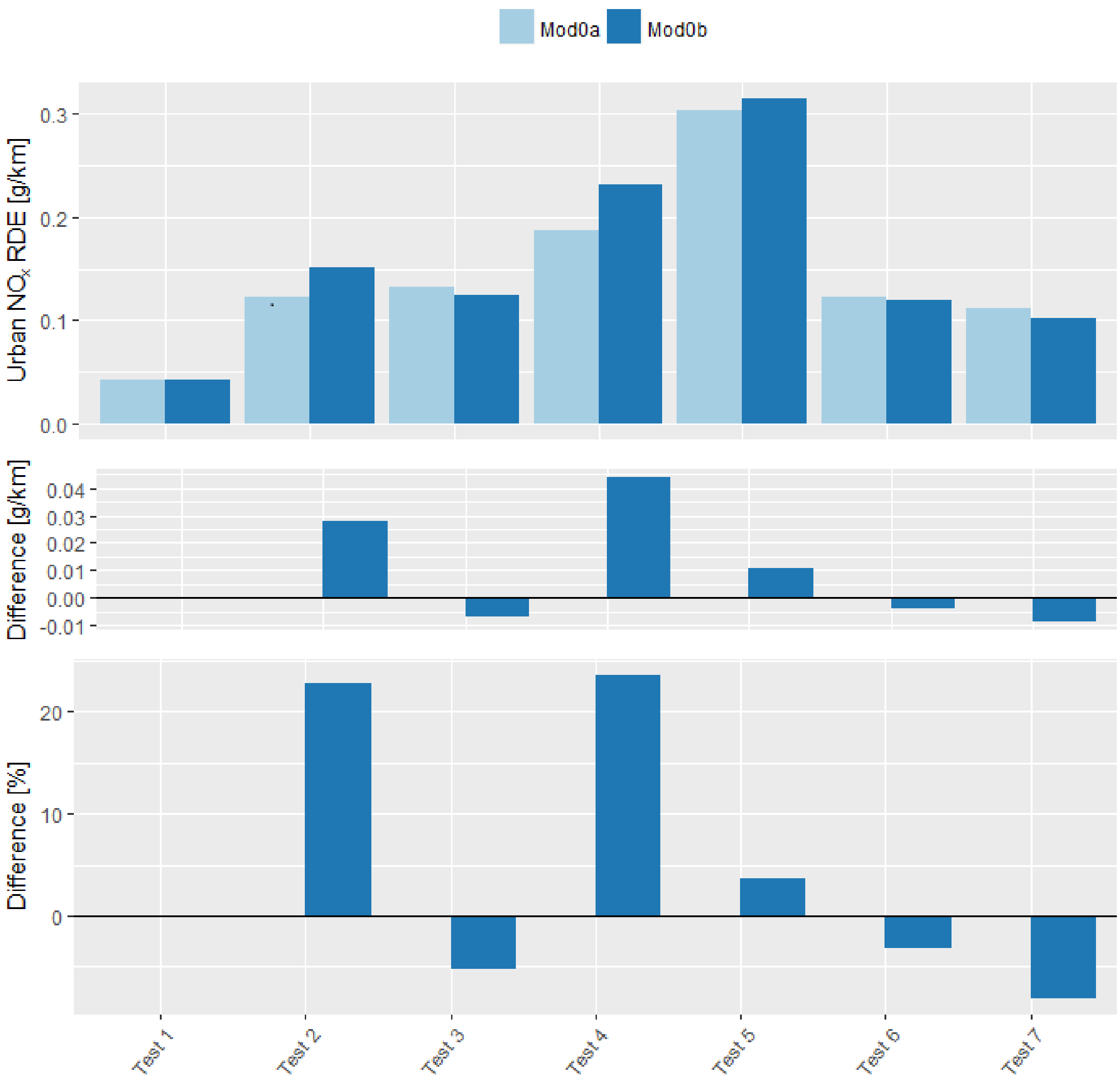

Figure 9: NO_X emissions after the evaluation of the urban part of an RDE trip with and without the inclusion of cold-start

Test 1 on the far left in Figure 9 shows no difference in the NO_X emissions between the baseline scenario (**Mod0a)** that excludes cold start and the cold-start inclusion into the normal RDE data evaluation (**Mod0b**) although this Euro 6 gasoline vehicle (see Table 2), like the other three vehicles included in our scenario analysis, showed higher NO_X emissions during cold start than during warm-engine operation. Moreover, only for 3 out of 7 tests, the inclusion of cold start into the normal RDE data evaluation (**Mod0b**) leads to an increase of the overall urban NO_X emissions.

For three tests, the overall urban NO_x emissions even decrease. This observation could potentially be explained by the weighting of cold-start windows. Cold start is typically characterized by elevated CO_2 emissions that, in turn, increase the average CO_2 emissions of cold-start windows and could thus lead either to an exclusion or a low weighting of the window-average NO_X emissions in the RDE data evaluation. The observation that the inclusion of cold start into the normal RDE evaluation could has no effect or even decreases the calculated NO_X emissions (although vehicles show higher NO_X emissions [mg/km] during cold start than during warm-engine operation) suggests that a simple inclusion of cold start into the RDE data evaluation may not cover cold-start emissions in a robust manner.

4.2.2 Modifications of RDE data pre-processing

The emissions effect of scenarios **Mod1a** (duplication of cold start at the beginning of a test), **Mod1b** (cutting the first 300 s of cold start from the beginning of a test and placing it in the middle of urban driving), and **Mod1c** (combination of **Mod1a** and **Mod1b**) are displayed in Figure 10.

The duplication of cold start at the beginning of a test (**Mod1a**) resulted in higher urban NO_X emission in 4 tests, and lower emissions in 2 tests compared to baseline scenario (**Mod0a**). The highest increase of about 50% in the urban NO_X emissions is observed for the second and fourth tests displayed in Figure 10. The Euro 6 gasoline car (Test 1) showed no difference in the NO_X emissions between scenarios **Mod0a** and **Mod1a**.

The shift of the cold start to the middle of the urban driving (**Mod1b**) resulted in higher urban NO_X emissions in 6 tests, and very slightly lower in 1 test relative to the baseline scenario **Mod0a**. The duplication of cold start and the subsequent placement of the duplicate into the middle of the urban part of a trip (**Mod1c**) resulted in higher urban NO_X emissions for 4 tests, and slightly lower NO_X emissions for 2 tests relative to the baseline scenario (**Mod0a**). For Test 6, no difference between the baseline scenario (**Mod0a**) and **Mod1c** was found.

Scenarios **Mod0b** and **Mod1b** both include cold start but at different location in the data stream. The urban NO_X emissions as evaluated with the moving averaging window method (EC, 2016a) tend to be higher when the cold-start section is included in the middle of urban driving (**Mod1b**) in 5 out of 7 tests compared to the scenario in which cold start is located at beginning of a test (scenario **Mod0b**).

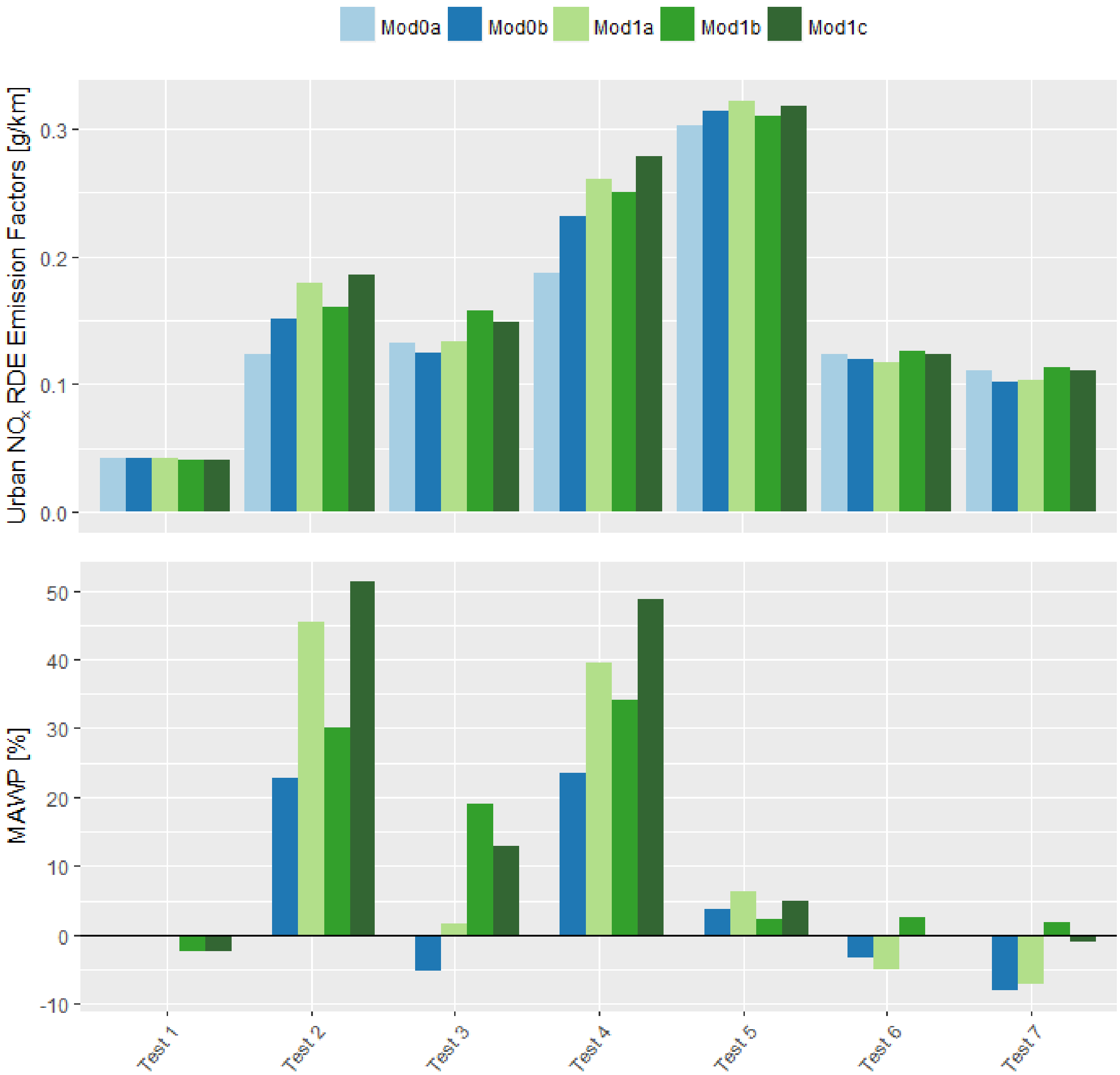

Figure 10: NO_X emissions effect of modifying the RDE data pre-processing

Scenarios **Mod1a** and **Mod1c** include two times the cold start section, but at different locations in the data stream. The urban NO_X emissions are higher when the second cold-start section is included in the middle of the urban part (**Mod1c**) in 5 out of 7 tests compared to the scenario where the duplicated cold-start is placed at the beginning of a test (**Mod1a**).

To conclude, our scenario analysis of modifications in the RDE data pre-processing suggests that pasting cold start in the middle of urban driving tends to increase the evaluated NO_X emissions relative to the default scenario in which cold start remains at the beginning of the test data cold. This observation could be explained by the larger number of windows covering the cold-start emissions if these are placed in the middle of urban driving. Still, the modifications of the data pre-processing did not yield a consistent increase in the urban NOx emissions for all tests. This observation (i) points again to the potential exclusion or weighting of cold-start windows if these show comparatively high CO_2 emissions and (ii) highlight the need to modify the moving averaging window method to cover cold start in a robust manner by the RDE test procedure.

4.2.3 Modifying the weighting of moving averaging windows

The emissions effect of scenarios **Mod2a** (constant weighting factor of 1 applied for the first 300 MAWs, regardless of distance-specific CO_2 emissions) and **Mod2b** (linearly decreasing weighting factor from 2 to 1 imposed for the first 300 MAWs) is presented in Figure 11.

Applying a weighting factor of 1 for the first 300 windows (**Mod2a**) increases the urban NO_X emissions for 4 tests and decreases the emissions for 3 tests relative to the baseline scenario **Mod0a**. Scenario **Mod2a** resulted in equal urban NO_X emissions for 5 tests than scenario **Mod0b** (inclusion of the cold start into the normal RDE evaluation of urban driving). This observation suggests that for these 5 tests, the CO_2 emissions of all windows covering the cold-start period were within the 25% primary tolerance around the CO_2 reference.

The application of a linearly decreasing weighting factor (**Mod2b**) resulted in higher urban NO_X emissions for 4 tests and lower emissions for 3 tests, relative to the baseline scenario **Mod0a**. The linearly decreasing weighting factor applied in scenario **Mod2b** results in higher urban NO_X emissions for 4 tests and lower emissions for 3 tests compared to the application of a fixed weighting factor of 1 in scenario **Mod2a**. This result suggests that the linearly decreasing weighting factor (**Mod2b**) amplifies the emissions effect observed in scenario **Mod2a** (application of a weighting factor of 1 for the first 300 windows) compared to the baseline scenario **Mod0a**.

To conclude, modifying the weighting of moving averaging windows ensures that all MAWs containing cold-start emissions are actually included in the calculation of the final RDE result. However, a modified weighting may not catch for all tests the excess NO_x emissions related to cold start. Overall increasing or decreasing urban NO_x emissions as the result of a modified weighting approach are possible as the application of, e.g., a fixed weighting factor changes also the warm-engine NO_X emissions that are contained in cold-start windows. If the warm-engine NO_X emissions contained in cold-start window are relatively low, the application of a fixed weighting could decrease the overall urban NO_X emissions, even if cold-start emissions are on average lower than the warm-engine emissions.

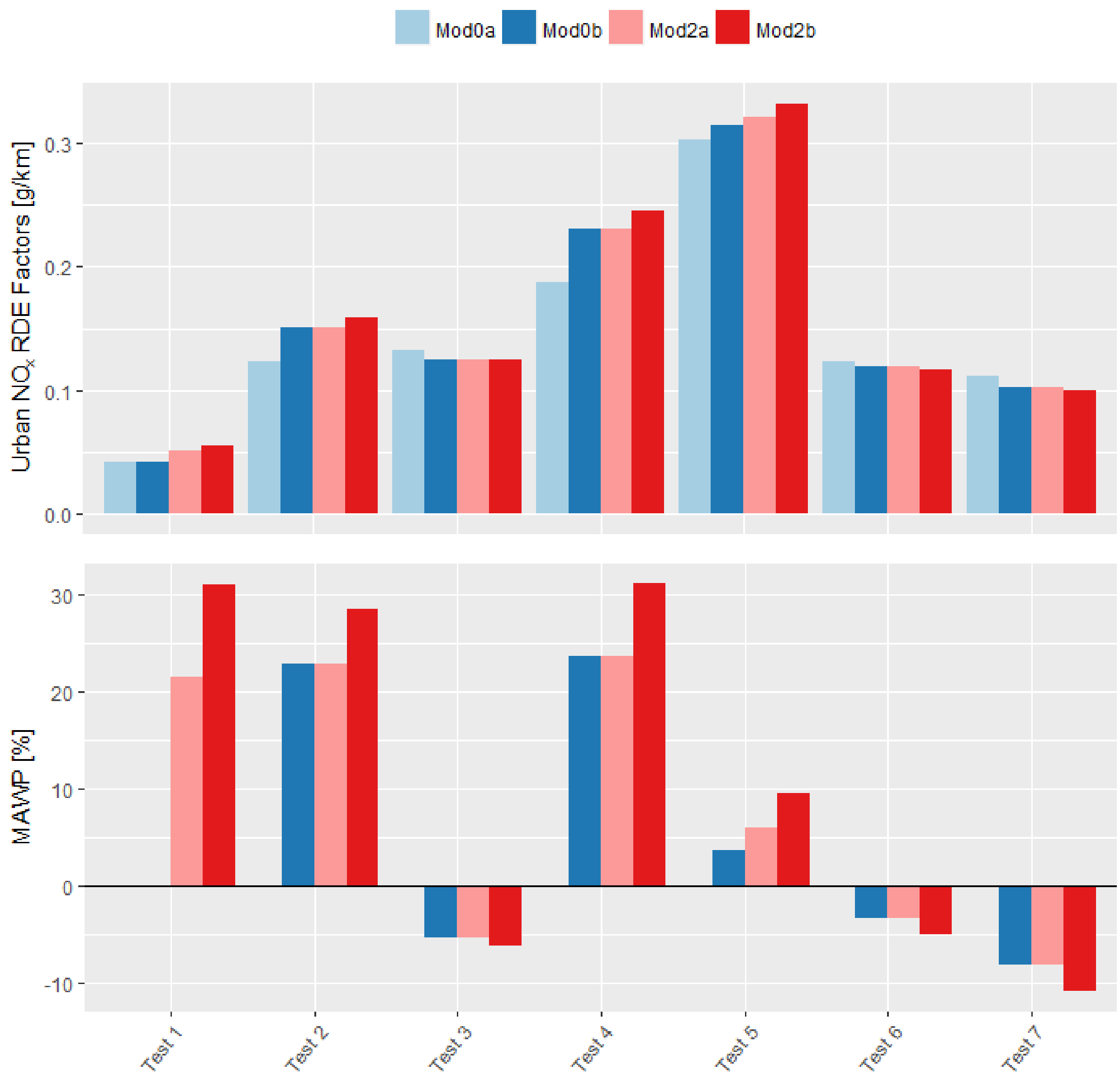

Figure 11: NO_X emissions effect of modifying the weighting of moving averaging windows

4.2.3 Combining modifications in the pre-processing and evaluation of NO_X emissions

Figure 12 depicts the NO_X emissions effect of combining scenario **Mod1c** (duplication of cold start in the middle of the urban driving) with the two scenarios that adapt the weighting of MAWs (**Mod2a** and **Mod2b**).

The duplication of cold start in the middle of the urban part combined with a weighting factor of 1 for the first 300 windows (**Mod3a**) resulted in higher urban NO_X emissions for 5 tests and slightly lower emissions for 1 test, relative to the baseline scenario **Mod0a.** The duplication of cold start in the middle of the urban part combined with a linearly decreasing weighting factor (**Mod3b**) resulted in higher urban NO_X emissions for 5 tests and slightly lower emissions for 2 tests, relative to the baseline scenario **Mod0a.** Scenario **Mod3b** tends to increase urban NO_X emissions to a large degree than scenario **Mod3a**; the former resulting in a maximum emissions increase of more than 60% for 3 out of the 7 tests, relative to the baseline scenario **Mod0a**.

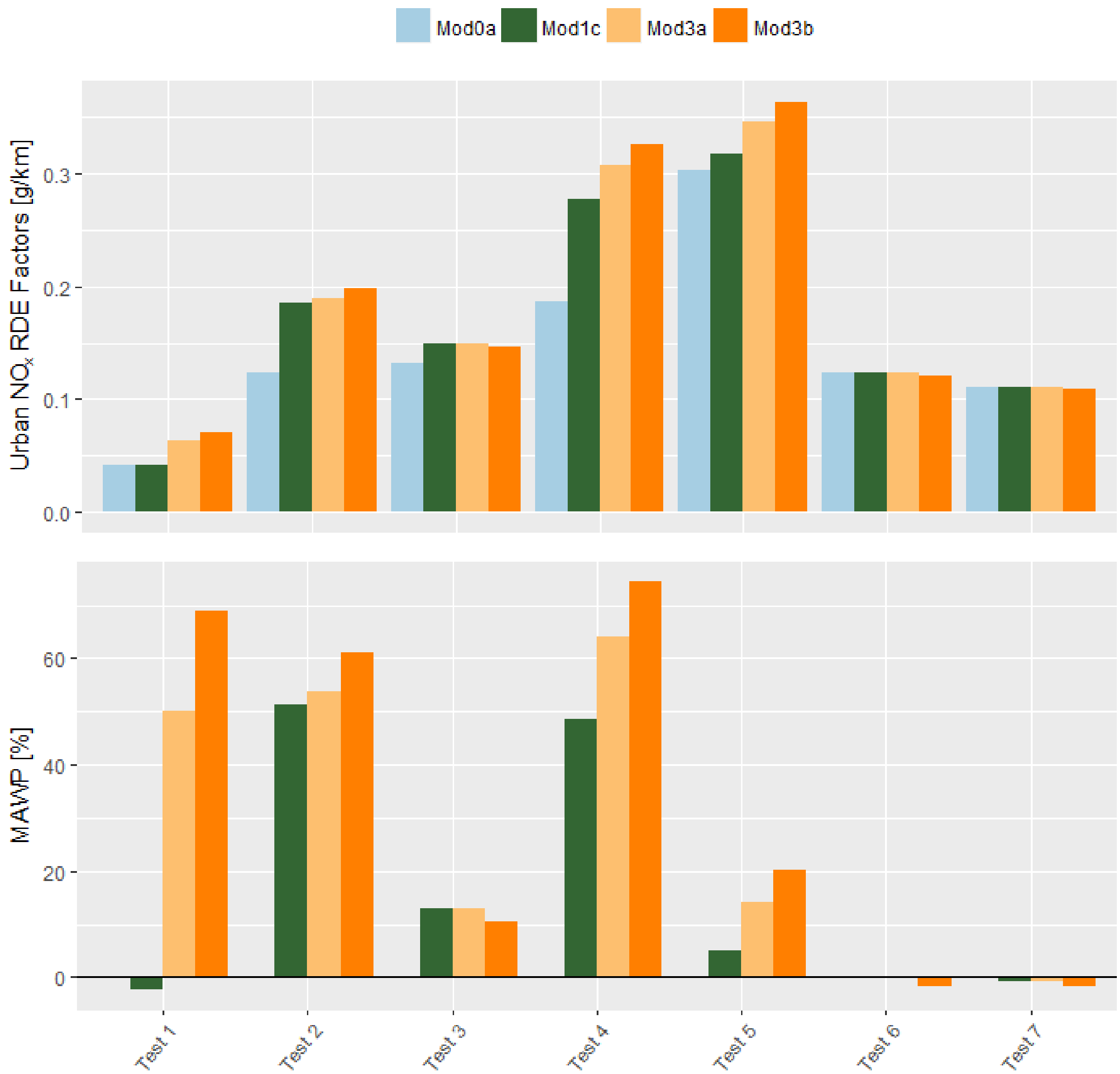

Figure 12: NO_X emissions effect of adapting the pre-processing of cold-start emissions and weighting of moving averaging windows

It appears that a combination of modifications of the RDE data pre-processing and the weighting approach for cold-start windows (as assessed by scenarios **Mod3a** and **Mod3b**) can better capture the excess cold-start NO_X emissions than an application of these two modifications separately. Further scenarios could be explored to substantiate this observation (see discussion in Section 5).

4.2.4 Summary of the scenario analysis

The percentage deviation between the NO_X emissions of each modelled scenario and the baseline scenario **Mod0a** can be expressed in terms of the moving averaging window performance (MAWP) and plotted as a function of the actual incremental cold-start emissions, expressed here as cold start performance (CSPI) of each tested vehicles (Figure 13, Table 9). A robust coverage of cold-start emissions would result in an approximately linear relationship between the NO_X emissions effect (MAWP) of a given scenario and the incremental cold-start NO_X emissions of a given vehicle (expressed in terms of CSPI).

Among the scenarios modifying the data pre-processing, scenarios **Mod1a** and **Mod1c** that include a duplication of the cold-start phase display the highest overall sensitivity to the cold-start performance of the tested vehicles. Among the scenarios modifying the weighting of moving averaging windows, the linearly decreasing weighting factor in scenario **Mod2b** appears to represent more accurately the cold-start performance of the tested vehicles than **Mod2a** does.

Yet, as discussed in Section 4.2.3, the scenarios combining modifications of the data pre-processing and the weighting of cold-start windows (**Mod3a** and **Mod3b**) showed the highest sensitivity to the actual cold-start performance of vehicles.

This conclusion is supported by a verification the statistical significance of the slope coefficients displayed in Table 9. Slope coefficients are generally not statistically significant (*p-value* > 0.1) and the coefficients of determination (R^2) low, given the data variability and the small data sample used for this analysis. This observation suggests that (taken individually) the applied modifications are generally not able to reflect the cold start emissions in a robust manner.

However, exceptions are scenarios **Mod2a** (*p-value* = 0.05), **Mod2b** (*p-value* = 0.036), **Mod3a** (*p-value* = 0.023) and **Mod3b** (p-value = 0.013) for which the slope coefficients are significant. The intercept coefficients for all scenarios are not statistically significant (p-value > 0.1), thus not significantly different from zero. Overall, our statistical analysis suggests that the assessment presented is indeed partial; additional modifications (next to those implemented and tested here) could be investigated to achieve a robust coverage of cold-start emissions within RDE.

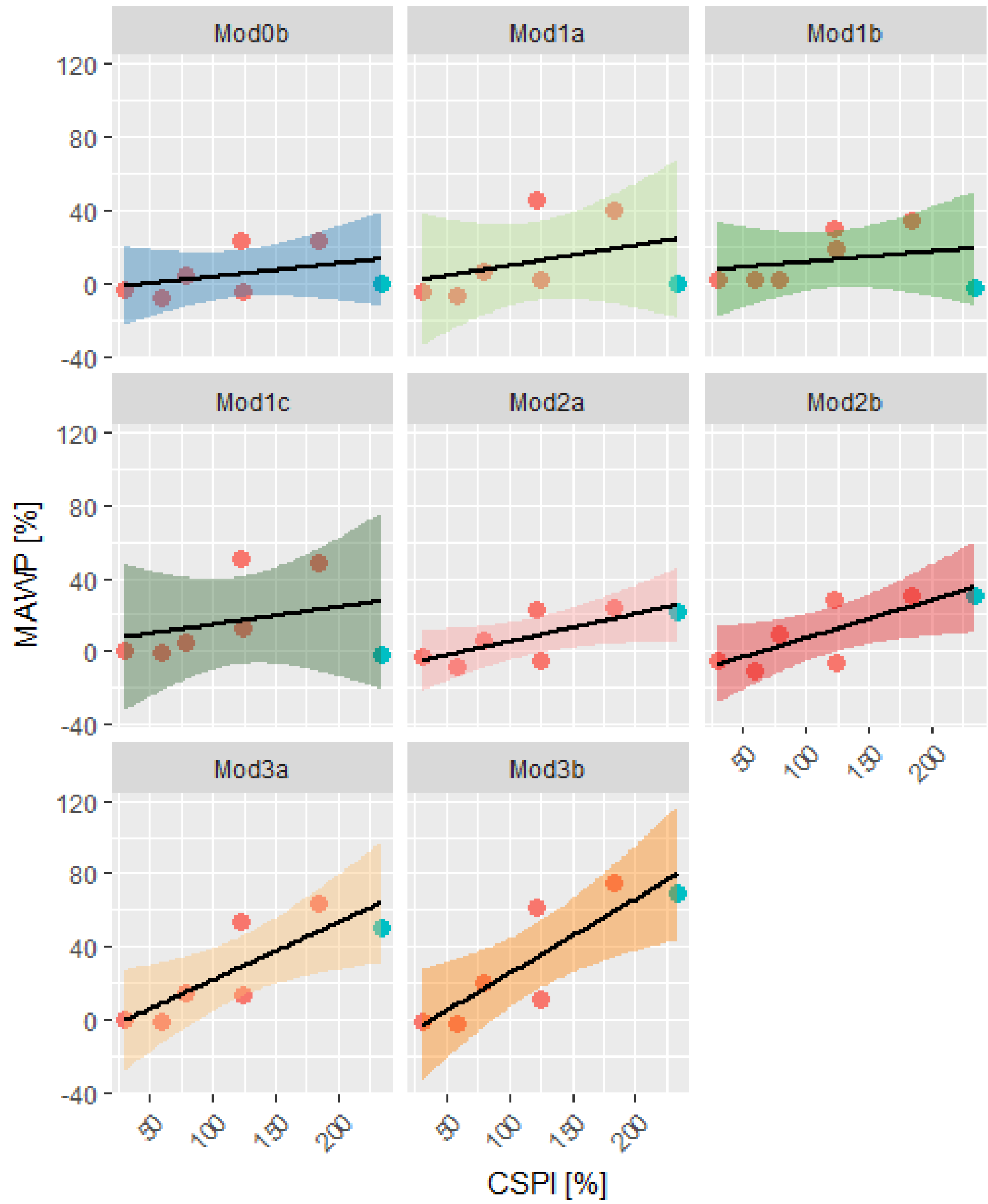

Figure 13: Relationship between MAWP and CSPI expressed through a simple linear model; blue dots depict the gasoline vehicle; red dots depict the diesel vehicles; coloured areas depict the confidence interval around the regression line

Table 9: Coefficients of the linear regression model fitted to explain MAWP as a function of CSPI

Scenario	Axis intercept [%]	Slope	R^2
Mod0b	-3.8	0.07	0.154
Mod1a	-1.4	0.11	0.129
Mod1b	5.8	0.06	0.072
Mod1c	4.8	0.10	0.087
Mod2a	-9.7	0.15	0.568
Mod2b	-13	0.21	0.619
Mod3a	-9.8	0.32	0.679
Mod3b	-15	0.41	0.742

5 Discussion and conclusions

5.1 General aspects

This report addresses two topics that are relevant for the establishment of a cold-start test procedure as part of the 3rd regulatory RDE package, namely (i) the distance typically driven by vehicle users between two consecutive cold starts and (ii) scenarios for a robust coverage of cold-start emissions by the RDE moving averaging window method. The analyses presented in this report on the two topics are intended to provide rationale for the stakeholder discussions in the RDE working group but should be considered preliminary. A more systematic collection and assessment of European driving data and an expansion of our scenario analysis through alternative modifications of the RDE data pre-processing and evaluation as well as the inclusion of additional vehicle test could add to the findings presented here.

We acknowledge that the number of data sources used for this analysis is rather limited in view of the diversity in driving patterns, vehicle characteristics, and socio-economic conditions within the EU. In occasions, we obtained data from the ‘grey’, non-peer-reviewed, literature and through personal communication. A major source of uncertainty represents the assumed minimum parking durations that are necessary to cool down the engine and after-treatment systems. As the temperature of these components at the start of a trip is a function of vehicle-specific parameters, ambient temperature, and the driving pattern prior to vehicle parking, cold-start frequencies may vary between vehicles and depending on season and geographical location. Yet, we regard the reviewed driving data to be suitable and our findings robust as a first order approximation of the typical distances driven in Europe between two consecutive cold starts.

Our scenario analysis on the modifications of the RDE data pre-processing and evaluation confirms that a simple inclusion of the cold start into the normal RDE data evaluation of Appendix 5 (Regulation 2016/427; EC, 2016a) might not capture for all vehicles and tests conditions the excess NO_x emissions from cold start in a robust manner. This observation can be attributed to the peculiarities of evaluating emissions data with the moving averaging window method (see Section 2). Given limited availability of resources, we have addressed here a limited number of scenarios but not yet, e.g., modifications of the actual calculation procedure of moving averaging windows (starting the calculation of moving averaging windows from the beginning of a test; applying a circular calculation of windows to ensure emissions data at the beginning and end of urban driving are contained in the same number of windows as data located in the middle of urban driving). Our preliminary analysis has mimicked the potential effects of such modifications to some extent. Yet, we see scope for assessing additional, and equally relevant, modifications in the future, e.g., a dedicated evaluation of emissions over the first moving averaging window or over a distance typically driven by vehicle users between two consecutive cold starts. Moreover, a circular calculation of windows could be investigated to understand the feasibility and potential emission effects of looping back the window calculation to the beginning of a test. Assessing this specific scenario will require some re-programming of the RDE data evaluation tools and could be combined with a fixed weighting factor of cold-start windows. Additional assessments could focus on the application of weighting factors directly to the cold-start emissions as part of the pre-processing of data. Moreover, our analysis has not addressed the second RDE data evaluation method (i.e., the power-binning method described in Appendix 6 of Regulation 2016/427). From the discussions in Section 2, we would expect that also power-binning in its current form may not be able to capture cold-start emissions in a robust manner. Further scenario analyses could investigate the feasibility of modifications of this method.

5.2.1 Conclusions on the driving distance between two cold-starts

Table 10 summarizes the data collected in our scoping review. Columns 3 and 4 display the mean and median trip distances. The frequency of parking events longer than, e.g., 3-8 h are shown in Column 5. Columns 6 and 7 then contain the distance between two consecutive cold starts, calculated by dividing the distances given in Columns 3 and 4 with the cold-start frequencies assumed in Column 5. Based on the analysis presented in Section 4.1 and the data summarized in Table 10, we draw the following conclusions:

- The distribution of trip distances tends to be positively skewed with the majority of trips being shorter than the arithmetic mean trip distance. This observation suggests that the median rather than the mean might represent best the general trend in the trip distances.
- Urban trips (based on all literature sources shown in Table 10: **7 ± 2 km (mean)** and **6 ± 2 km (median)**[12]) tend to be shorter than the overall average trip driven in urban and extra-urban environments (based on all literature sources shown in Table 10: **10 ± 3 km (mean)** and **8 ± 3 km (median)**).
- Data on the frequency of cold-starts are scarce; the actual frequency depends, e.g., on the assumed parking duration, ambient temperature, operating conditions prior to vehicle parking, and the vehicle-specific design of engine and after-treatment technologies. Based on the data presented by De Gennaro et al. (2014), Donati et al. (2015), Paffumi et al. (2015), Karlsson (2013), and HBEFA 3.2 (Kühlwein, 2016) and under the assumption that a cold start occurs after vehicle parking of some 3 h to 8 h, we conclude that as a first-order approximation, **27 ± 5% of trips may contain a cold start.** The findings of Klein et al. (2015), according to which 60% of trips in the Netherlands contain a cold start, appear to include parking times substantially shorter than 3 h.
- Averaging the data displayed in Columns 6 and 7 suggests that in Europe the **distance between two consecutive cold starts is 36 ± 16 km (mean)** and **30 ± 13 km (median)**. If only urban trips are considered, the **distance between two consecutive cold starts reaches 25 ± 16 km (mean)** and **27 ± 8 km (median)**.
- The choice of a 3-8 h parking duration to differentiate between cold-start and warm-start trips accounts (to some extent) for the cold-start definition in the RDE test procedure. In real-word driving, also substantially shorter parking durations may lead to a cold start, e.g., vehicles are driven over comparatively short trips or if driving and parking occur at lower ambient temperatures that the 15°C assumed in Figure 3. Additional research considering the actual cool down of after-treatment technologies of a sample of vehicles is necessary to verify our results.
- We consider our results to represent conservative estimates on the distance vehicle users actually drive between two consecutive cold starts. More detailed scenario analyses incorporating additional data could verify the conclusions of this report.

[12] Calculated as the mean and the standard deviation of individual medians presented in Table 10.

Table 10: Overview of results; numbers in normal type setting obtained from the respective sources; numbers in italics calculated by the authors of this report

Source	**Country**	**Mean trip distance [km]**	**Median trip distance [km]**	**Frequency of daily cold start; percentage of trips containing cold starts[(a)]**	**Scenario calculation: Mean distance between two consecutive cold starts**	**Scenario calculation: Median distance between two consecutive cold starts**
De Gennaro et al. (2014); Paffumi et al. (2015)	Italy (Modena and Florence)	8 ± 3 (urban trips)	8.4 (urban trips)	20% (parking ≥6h) 30% (parking ≥3h, coolant <30 °C)	*40 ± 15* *27 ± 8*	*42,30*[(c)] *28, 20*[(c)]
Donati et al. (2015)	Various cities in 6 European countries	7.8 (urban trips, electric)	4.8 (urban trips, electric)	20% (parking ≥6h) 27% (parking ≥3h, coolant <30 °C)	*39* *29*	*24* *18*
Klein et al. (2015)	The Netherlands	14.5 (all trips)		60%	*24*	
Klein et al. (2015)	The Netherlands	4 (urban trips)		60%	*7*	
Klein et al. (2015)	The Netherlands	12 (extra-urban trips)		60%	*20*[(b)]	
Karlsson (2013)	Sweden	*12 ± 6*	*11*[(d)]	25%	47 ± 25	42[(d)]
Steven (2016)	WLTP data base	10.5 (all trips)		*20% (parking ≥6h)* *27% (parking ≥3h, coolant <30 °C)*	*53* *39*	
ACEA (2016)	BMVI data for Germany			*≥2*	*≥19*	
Misc. data analysed by JRC	Various European countries	14 ± 5 (all trips)	12 (all trips)	*20% (parking ≥6h)* *27% (parking ≥3h, coolant <30 °C)*	*70 ± 25* *52 ± 19*	*60* *44*
T&E (2016)	Various European countries		6 (urban trips)	*20% (parking ≥6h)* *27% (parking ≥3h, coolant <30 °C)*		*30* *22*
HBEFA3.2	Various European countries	8.3 ± 1.6 (all trips)	4.9 (all trips)	31% (mean, parking ≥8 h) 35% (median, parking ≥8 h)	*27 ± 8* *24 ± 5*	*16* *14*

(a) Entries in *italics* are assumed or calculated by the authors of this report.
(b) Klein et al. (2015) specify the number of cold starts per passenger car kilometre for rural roads to be approximately 0.005. Personal communication with Ligterink (2016) suggests the actual number of cold starts per passenger kilometre is in fact 0.05, suggesting a driving distance between two cold-starts of 20 km.
(c) Calculated based on the frequency distribution displayed in Figure 2.
(d) Representing the median value of the mean driving distances covered by each individual car between parking durations of 6 h or longer.

5.2.2 Conclusions on the scenario analysis – cold-start inclusions

From the scenario analysis presented in Section 4.2, we draw the following conclusions:

- Modifying the data pre-processing by duplicating or shifting cold-start emissions to the middle of the urban part of a trip (**Mod1a**, **Mod1b**, **Mod1c**) generally increases on average the overall urban NO_X emissions but may also result for individual tests in decreasing calculated emissions compared to the baseline scenario **Mod0a** (exclusion of cold start). Taking into account that all vehicles included in our analysis showed higher NO_X emissions during cold start than during warm-engine operation, we conclude that these proposed modifications of the RDE data pre-processing can improve the coverage of cold start by the RDE data evaluation but are, by themselves, insufficient to capture cold-start emissions in a consistent manner.
- Modifying the weighting of moving averaging windows by assuming a constant or linearly decreasing weighting factor for the first 300 windows (**Mod2a, Mod2b**) likewise tends to increase on average the overall urban NO_X emissions but may also decrease the urban NO_X emissions for individual trips compared to the baseline scenario (**Mod0a**). For several tests, the modification of the weighting approach amplified the emissions effect (i.e., the observed increase or decrease of the overall urban NO_X emissions) observed for the inclusion of cold-start inclusion into the normal RDE data evaluation (scenario **Mod0b**). Moreover, applying a linearly decreasing weighting factor (from 2 to 1 for the first 300 windows in scenario **Mod2b**) amplified the emission effects observed for a constant weighting factor of 1 (**Mod2a**). Therefore, modifying the weighting of windows may at occasions increase the coverage of cold start by the RDE data evaluation but is, by itself, insufficient to capture cold-start emissions in a robust and consistent manner.
- A combination of modifications in the data pre-processing (e.g., scenario **Mod1c** that duplicates cold start) and the data evaluation (e.g., scenarios **Mod2a** and **Mod2b** that apply a constant or linearly decreasing weighting factor for cold-start windows) as it is modelled by scenarios **Mod3a** and **Mod3b** shows the highest responsiveness to the actual cold-start emissions performance of vehicles. This observation suggests that a combination of modifications in the data pre-processing and evaluation might capture the cold-start emissions in a more robust manner than applying the proposed modifications individually. Yet, our analysis suggests that even a combination of the proposed modifications may not capture the incremental cold-start emission of *all* vehicles. We thus propose to complement our analyses by additional modification scenarios in the future.
- Any of the analysed scenarios could be implemented without major modifications of the existing provisions of Regulation 2016/427 (EC, 2016a).

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