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TNO report

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Chase car study: driving behaviour in the Netherlands, Belgium, France and Germany

Technical report under the Assessment of the strengths and weaknesses of the new Real Driving Emissions (RDE) test procedure (TNO 2016 R11227)

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Samenvatting

In de loop van 2015 is er besproken welk rijgedrag uitgesloten zou worden van de nieuwe RDE test voor voertuigemissies op de weg. In het bijzonder zou agressief rijgedrag uitgesloten worden op basis van de fysieke versnellingen van het voertuig tijdens de testrit. Het oorspronkelijke voorstel uit de technische commissie in Brussel strookte niet met het beeld op de Nederlandse weg. Zowel normaal Nederlands rijgedrag voor emissiefactoren, als gemiddeld rijgedrag in emissiemetingen, viel gedeeltelijk buiten de grenzen in het voorstel. Op basis van dat voorstel zou ongeveer de helft van al het rijgedrag in de stad uitgesloten worden als te agressief. De resultaten van een Nederlandse studie uit 2015 voor rijgedrag voor emissiefactoren voor de luchtkwaliteitsmodellen is daarom ingebracht. De uiteindelijke RDE wetgeving reflecteert deels deze inzichten. Maar de zorg bleef bestaan waarom de Nederlandse studie afwijkend was van het gevestigde beeld in bij experts in Brussel.

Het Ministerie van Infrastructuur en Milieu heeft daarom een extra studie gelast om uitsluitsel te geven over een aantal vragen omtrent de verschillen in inzichten. Ten eerste is deze studie uitgevoerd in Nederland, Frankrijk, België, en Duitsland om te bepalen of er nationale verschillen zijn in rijgedrag. Dat bleek inderdaad het geval. In België wordt agressiever gereden dan in de andere landen, en in Duitsland wordt het tamst gereden. Rijgedrag studies uit een enkel land hebben daarom geen directe relatie tot het gemiddelde Europese beeld, maar zijn wel belangrijk om lokale effecten goed te begrijpen. Ten tweede is de onderzoeksmethode van het volgen van willekeurige auto’s op de weg in twijfel getrokken. Met behulp van een geïnstalleerde radar in het volgvoertuig is de snelheid van de gevolgde auto’s ook achterhaald. De volgauto rijdt gemiddeld iets minder agressief dan de auto’s die hij volgt, maar de verschillen zijn erg klein. Er zit wel enige spreiding op deze resultaten, maar die kunnen ook het gevolg zijn van de tekortkomingen aan deze nieuwe methode om de snelheid van beide voertuigen te bepalen. Ten derde, de onderliggende aanname onder de huidige wetgeving is, dat alle voertuigen hetzelfde rijden, ondanks het verschil in motorvermogen. Voor bestelauto’s, zeker bij volle belading, is het duidelijk dat dat niet zo is. Deze voertuigen kunnen fysiek niet agressief rijden, in termen van de versnellingen, volgens de RDE wetgeving definitie. Aan de andere kant zijn er aanwijzingen dat het aanwezige vermogen, in hoog vermogen voertuigen, deels gebruikt wordt om sneller op de gewenste snelheid te zijn, en daarvoor iets harder te accelereren.

De methode van het achtervolgen van auto’s op de weg is, in principe, goed om een beeld te krijgen van normale rijgedrag op de weg. De keuze van de chauffeur, de instructies, en het voertuigen spelen daarin een belangrijke rol. Uit deze studie volgt dat de huidige definitie in de RDE wetgeving van de grens van agressief rijden redelijk geschikt is voor Nederland en Frankrijk, maar mogelijk te streng voor normaal Belgisch rijgedrag. Deze conclusie is gebaseerd op de onderliggende norm dat 95% van het normale rijgedrag binnen de grenzen van de RDE testregime ligt. Er zijn wel gebleken bezwaren aan een uniforme definitie van agressief rijgedrag gezien de grote variatie van voertuigen, van de zware bestelauto’s tot voertuigen met een zeer hoog vermogen, die allemaal onder dezelfde RDE wetgeving vallen.

Summary

In the course of 2015 the driving behaviour boundaries for RDE legislation was discussed and proposed in a technical commission in Brussel. In particular aggressive driving was to be excluded from the RDE test. The original proposal did not reflect the experiences with normal driving in on-road testing in the Netherlands. The proposal would mean typically half of the normal urban trips would result in invalid RDE tests. This boundary for aggressive driving is based on the 5% of the hardest accelerations in a trip, for different velocity ranges. The results of study from 2015 of driving behaviour for the Dutch national air quality model and emission inventories was brought in to the discussion, which showed a different range of driving behaviour than was the common understanding at the time. Consequently, the original proposal was adapted to reflect partly the Dutch results.

The concerns regarding normal and extremes in aggressive driving remained. Moreover, the method of using a professional driver, following random cars on the road was questioned as a valid approach to determine driving behaviour. A chase car could result in more hard acceleration in order to follow cars in front. Also the Dutch driving behaviour may not reflect the European average. In order to establish the legitimacy of the first result, the Ministry of Infrastructure and Environment ordered a second study, to address the concerns raised in Brussel. This study is reported here.

The same driver also drove in Belgium, France and Germany. Moreover, an in-car radar was used to measure relative velocity of the chase car and the car in front. In the Netherlands a licence plate camera is used to determine the power-to-mass ratio of the cars in front, to see if discernible differences in driving behaviour could be correlated with the different engine powers of vehicles on the road. It turned out that driving behaviour in Belgium is more aggressive, according to the RDE definition, than in the Netherlands or France. On the other hand driving behaviour in Germany is less aggressive. The effect of power-to-mass differences could not be established with confidence. On the other hand, the professional driver in this study drove slightly less aggressive than the cars he followed. It can be concluded that the car chase method can serve as a method to establish the driving behaviour on the road. This conclusion does not automatically carry over to any other chase car study.

This report also summarizes results on the effect of payload on the driving behaviour with light commercial vehicles, or vans. With a high payload, large vans cannot drive aggressively according to the RDE definition, based on the maximal accelerations during the trips. Given the power-to-mass ratios, in some cases the RDE boundary is physically not attainable for many heavy-loaded vans. This is unlike passenger cars where the engine power is generally sufficient to drive aggressively according to the RDE definition.

The current RDE boundary would exclude a limited number of trips recorded in the Netherlands. In Belgium more trips would be excluded. In the uncertainty band also a few trips in France might be invalid. Only in Germany all trips were clear of the aggressive driving boundary of the current RDE legislation.

Contents

1 Introduction

The European RDE (Real Driving Emissions) legislation will come into force as of 1 September 2017 and its aim is to secure low real-world emissions of future Euro 6 passenger cars and light duty vans in 'normal use'. Following the logic of the design of the legislation, RDE should cover the full span of normal driving behaviour frequently encountered in the EU. On the other hand, to prevent vehicles from being tested under extreme driving conditions, like excessively high dynamics or consistently slow driving, boundary conditions have been introduced in the RDE-legislation to define the acceptable span of 'normal driving'. The boundary conditions are expressed in thresholds or limit values against which RDE test performed will be assessed on their validity. The levels of the limit values have been extensively discussed during the development of the second RDE package.

The actual value of the upper limit for excessively aggressive driving was a compromise between the results deduced from the WLTP database of driving behaviour and the results of a more of recent study of TNO in 2015 in the Netherlands to update the driving behaviour underlying the national emission factors for the air quality models.[1]
The TNO study was based on the **car chase method**. Especially for urban driving the Dutch results show a much higher upper limit for normal driving than the result from the European part of the WLTP database. This database consists of driving data collected for the driving cycle development resulting in the new WLTC (World-harmonised Light-duty Test Cycle). Therefore, the results were somewhat unsatisfactory because of the large unexplained gap, between the two data sources: European data from 2010 and Dutch data from 2015.

The Dutch Ministry of Infrastructure and the Environment sponsored an additional study to settle outstanding questions raised in Brussels:

1. Is Dutch driving behaviour different from other European countries?
2. Does the car chase method used in the Dutch study generate a bias towards more aggressive driving (hard accelerations and hard braking) to keep a constant distance in the chase?
3. Does the short periods of following a car and the switches from one car to another during a trip lead to a higher statistics of aggressive driving, as one car out of a few cars followed may be responsible for all the highest data in the evaluation of aggressive driving.
4. Is the increase in rated engine power responsible for a change in driving behaviour? Is the driving behaviour with high powered cars different?

This technical report gives an introduction to the new chase car study performed in 2016 (Chapter 2). In Chapter 3 the results are analysed with respect to the RDE boundaries. In Chapter 4 older data, from on road testing, of light commercial vehicles is set against the RDE boundaries. The accuracy of the car chase approach in this study is analysed with the radar data collected during the test program.

[1] TNO report 2016 – R 10188 On road determination of Dutch driving behaviour for vehicle emissions.

2 Set up of the new chase car study

The car chase method comprises following random cars on the road, on a generic route from one location to the next. If the chase car itself repeats the driving pattern of the car in front, and the changes from one car, to be followed, to the next are smooth and not too frequent, the driving behaviour of the car should be a good representation of ’normal’ driving behaviour on the road. Moreover, this driving should be more representative than the driving of an average driver. A small part of driving contributes substantially to total emissions. If only the average driver and his average driving is covered, these small but important parts may be excluded.

The study in Spring 2016 was specifically designed to supply answers to the questions summarized in Chapter 1.

The following items were included in the test:

1. The driving included trips in Belgium, France, Germany and the Netherlands, to compare the driving behaviour in the different countries.
2. The car was instrumented with a 77GHz Continental automotive radar to ensure that not only the velocity of the chase car itself, but also the velocity of the car in front was monitored with good accuracy.
3. The car was instrumented with a camera to record license plate data in the Netherlands to investigate the dependencies in driving behaviour with the power-to-mass ratio of the vehicles.
4. Velocity of the vehicle is determined from the ABS and it corresponds to the rotation velocity of the wheels calibrated with the global distance according to the GPS coordinates.

The chase car was selected to have sufficient power to be able to follow all the vehicles on the road. All trips were driven by the same experienced and well instructed driver in order to prevent the introduction of a bias. In particular a driver with little confidence would follow at a short distance and may brake and accelerate harder than the car that is being followed. An experienced driver will leave enough distance and will allow reaction time to change velocity subject to the behaviour of the car in front. The chase car was instrumented with a radar to study potential bias. The check of the data afterwards confirmed no bias was introduced.
The chase car used in this study was the Mercedes Benz C220 Bluetec, which emission performance are reported in a different study.[2]

[2] TNO Report 11123, Review into the relation between ambient temperature and NOx emissions of a Euro 6 Mercedes C220 Bluetec with a diesel engine, Gerrit Kadijk, Norbert Ligterink, and Richard Smokers (2016).

3 The criteria of excessive driving behaviour

3.1 The $v*a_{pos}$(95%) criterion of aggressive driving

The criterion commonly used to express the level of aggressive driving is $v*a_{pos}$(95%)[3]. This criterion was developed in the 1990s as one of the trip characteristics, to classify driving behaviour for vehicle emissions. With an increase of $v*a_{pos}$(95%) the emissions of older vehicles, like Euro-2 and Euro-3, increase dramatically. The 95% percentile is to ensure the result is independent of the length of the trip. The longer the trip, the higher the probability that a high $v*a_{pos}$ value is encountered. The 5% highest values remain, more or less, the same value. Only the number of samples that make up this 5% grow with the length of the trip.

The general assumption underlying the RDE legislation is that the power-to-mass ratio does not affect the driving style, and that despite the high v*a attainable with high powered vehicles, these high values are seldom reached in normal driving. The limits for aggressive driving were set at a fraction of the maximal attainable values for a modern average European car, which have considerable engine power, compared to older cars. The 2015 study[4] of driving behaviour in the Netherlands showed different results. Accelerations, in particular accelerations at lower vehicle speeds turned out to be much higher than assumed on the basis of average driving behaviour derived from the WLTP database. The value derived from the WLTP data base was the reference for the initial proposal of the European Commission in 2015. If this value was adopted half the urban trips in the Dutch test program of normal driving behaviour would disqualify as a legislative RDE test trip.

[3] v*apos(95%) is defined as the value of the 95% percentile of the highest values among the positive values of velocity times acceleration. This value is determined separately for three velocity ranges: 0-60 km/h, 60-90 km/h, and above 90 km/h.
[4] On-road determination of Dutch driving behaviour for vehicle emissions, Norbert E. Ligterink, TNO report 10188 (2016).

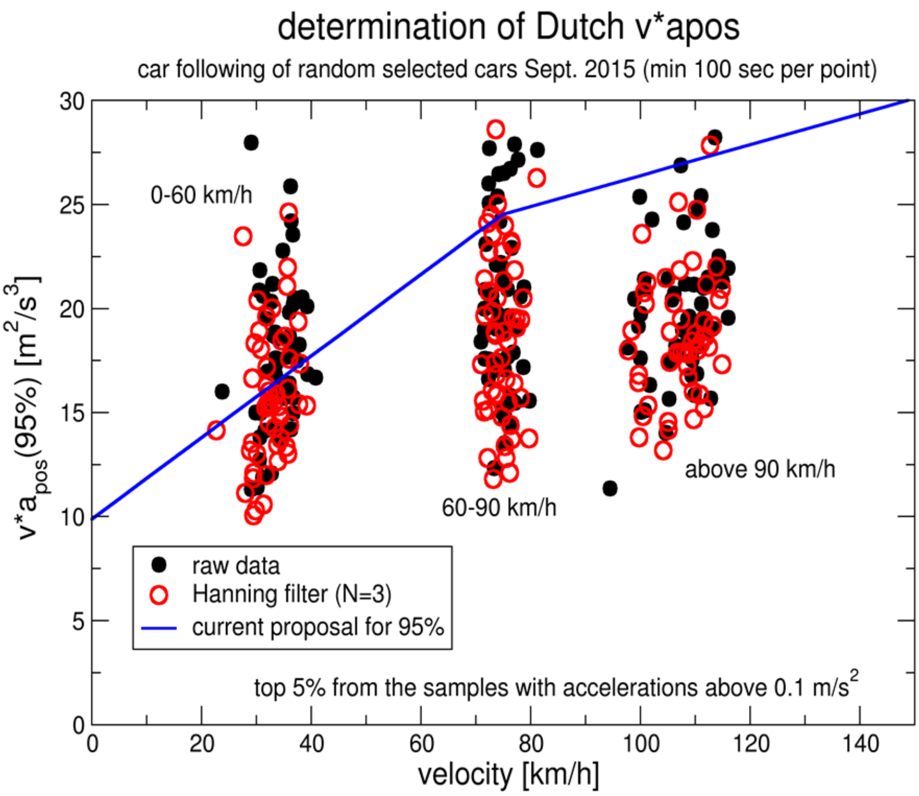

Figure 1: The initial test results presented in the autumn of 2015 set against the proposal (blue line) from the RDE expert group of Summer 2015. Every point is a trip, and points above the blue line are invalid RDE trips. Especially at lower speeds about half of the test trips would disqualify if this boundary was used in RDE. Data smoothing with a Hanning filter, as was proposed, affects the results only slightly. The red circles correspond to the, then proposed, smoothing of the data.

Consequently, the proposal of the Commission in October 2015 for the $v*a_{pos}(95\%)$ limit was adapted to a line which excluded fewer trips. This proposal was adapted in Commission Regulation 2016/646 of 20 April 2016. The regulation includes a provision that the limit may be adapted on the basis of new data.

The current legislation (2nd RDE package) states that a trip is valid for $v*a_{pos}(95\%)$ if for all three speed bins:

If $v_{bin\text{-}average} < 74.6$ km/h:

$$v*a_{pos}(95\%) < 0.136*v_{bin\text{-}average} + 14.44$$

else

$$v*a_{pos}(95\%) < 0.0742*v_{bin\text{-}average} + 18.966$$

In this report the soundness of this limit is tested.

3.2 The RPA criterion of tame driving

Next to a limit of aggressive driving, RDE also contains a criterion for tame driving. This criterion is the relative positive acceleration (RPA) and yields the average acceleration during the RDE trip. If all accelerations are very moderate or limited, the value is low. Such situations arise for example if a car does not have any stop, but long stretches of near constant driving.

4 Driver experiences and test routes

The test program was set up along the same lines as the study from 2015, with a license plate camera and a radar installed additionally. The most important goal of the study was to collect comparative data from different countries.
The test trips were executed in the Netherlands, Belgium, France and Germany. Busy metropolitan areas, such as Antwerp, Brussel, Paris and Bonn were visited. Each country was covered in a three day trip, with overnight stops, on weekdays. A small part of the distance was covered in Luxembourg, but for this country no observations are noted down here. This section describes the most important aspects affecting driving behaviour observed by the test driver during execution of the test program. It covers urban driving, rural driving and motorway driving and deals with four elements per road type: infrastructure, traffic rules, road traffic congestion and driving behaviour intrinsic to the country at hand. Specific conditions, such as weather and routes are given at the end of Chapter.

4.1 Driver experiences

4.1.1 Urban driving

4.1.1.1 Infrastructure

In the Netherlands and Germany, roads typically are well-designed, with clear road markings and road signs. In general, the quality of the road surfaces is good and the roads are well-maintained. In Belgium, urban roads are generally of a lower quality compared to the Netherlands and Germany and the urban roads show more winding compared to the Netherlands, Germany and France. Some Belgian cities have short stretches of four-lane roads. The test driver noted that in Brussels the roads are better structured than in most other Belgian cities.

4.1.1.2 Traffic rules, road signs and traffic lights

Traffic lights in the Netherlands and Germany are positioned so that they are hard to ignore and the stop position is clearly indicated. In Germany, traffic lights go from red to orange to green, instead of from red to green at once, as is the case in the Netherlands, Belgium and France – and most European countries. In Belgium and France, traffic lights in some cases are positioned in a way that they cannot be easily observed and the stop position is not always (clearly) indicated (i.e., no stop lines). In Germany, environmental zones apply in many cities. Also, Germany speed cameras are ubiquitous and often camouflaged in green colour so they are hard to observe against the road-side trees.

4.1.1.3 Congestion

Urban traffic intensity in the Netherlands is high. As a result, vehicles are driven at relatively low speeds and accelerations. In Germany, the situation is comparable, albeit a bit less crowded. Urban driving in France is a highly demanding task as the traffic intensity is very high. Traffic jams are the rule here rather than the exemption, and motorists tend to fill every space that comes available. As a result, traffic junctions are regularly blocked, leading to chaotic traffic situations. In Paris, this situation is most exemplary, and, adding to that, traffic in Paris is characterized by the great number of motorcycles, mopeds and scooters which drive in between the lanes of queueing cars at relatively high velocity.

4.1.1.4 Driving behaviour
Motorists in the Netherlands and Germany, in general, show relatively disciplined driving behaviour. In the city, most of the time the speed limits are well respected. The same goes for France, although there, due to the high traffic intensity, it is simply not possible to exceed the speed limits. In Belgium, compared to Germany and the Netherlands, motorists drive less disciplined and the traffic situation in the city appears to be a bit more chaotic. The motoring skills seem a bit lower than in the other countries. High accelerations after the traffic light shows green were observed regularly in Belgian cities.

4.1.2 Rural driving

4.1.2.1 Infrastructure
In the Netherlands, rural roads contain many roundabouts. Also, the road design and the flatness of most of the roads makes overtaking relatively easy. In general, the quality of the road surface is high. The same goes for German rural roads, which, compared to the Netherlands, have longer distances without traffic signs or traffic lights and contain few bends. They do, however, show more height differences, which makes overtaking more difficult. It appears that Germany recently started the introduction of roundabouts in rural roads as most of them are relatively new. In Belgium, rural roads show a lower-quality road surface and less roundabouts than the Netherlands, France and Germany. Belgian rural roads are also characterized by many height differences and the relatively many junctions with traffic lights and more bends when compared to Dutch, German and French rural roads. In Belgium, and more specifically in the Antwerp region, cars get stuck behind slow traffic, i.e., trucks, relatively often. French rural roads are comparable to German rural roads. Both German and French rural roads are, however, relatively narrow compared to Dutch rural roads. In all countries, rural roads most of the times are two-lane.

4.1.2.2 Traffic rules, road signs and traffic lights
Speed limits on Dutch rural roads is generally 80 km/h. In France, the road type is not always clearly indicated. The speed limit on French rural roads is 90 km/h, as is the case in Germany. In Belgium the rural speed limit was 90 km/h at the time.

4.1.2.3 Congestion
Traffic on Dutch rural roads is heavy compared to the other countries. It must be noted, however, that most of the distance was covered in the Randstad, the densely populated Western part of the Netherlands. Due to the heavy traffic, acceleration are generally low.

4.1.2.4 Driving behaviour
On Dutch rural roads, driving is disciplined and speed limits are generally well respected – in part due to the high traffic intensity. In Germany and France, speeding is observed more frequently, especially when cars drive ‘alone’ – which occurs more often than in the Netherlands. Belgian driving behaviour on rural roads is comparable to the Belgian urban driving behaviour.

4.1.3 *Motorway driving*

4.1.3.1 *Infrastructure*

Generally speaking, motorways in the Netherlands and Germany are of a high quality. The same goes for France, where especially the péage-roads are of good quality. As with urban and rural roads, Belgian motorways generally have a bit lower-quality road surface and their lining is less clear. Most motorways encountered have four to six lanes. In crowded areas, this number sometimes increases to as much as ten. No large differences between countries exist in this respect. The Dutch motorway network is dense and compact, compared to other countries.

4.1.3.2 *Traffic rules, road signs and traffic lights*

In the Netherlands, three motorway speed limits exist: 100, 120 and 130 km/h. Matrix signs provide information on traffic jams that start to exist. In France, 100 and 130 km/h are the most frequently applied limits, as is the case in Germany. Germany does however provide motorway stretches that have no speed limit. In Belgium the speed limit is 120 km/h, except for some control areas.

4.1.3.3 *Driving behaviour*

Due to the traffic intensity in the Netherlands, the driving speed often is around 100 km/h, and no room for passing other cars exists. As a result, motorists often keep the lane they are driving, i.e., they often do not keep right. This leads to tailgating happening in the Netherlands relatively frequently. In Germany, motorists keeping right are encountered more frequently and also the speed limits are well obeyed. Some motorists do indeed make advantage of the road segments without speed limit, bringing their vehicle to high speeds. Other motorists are well aware that there may be high-speed cars around and therefore keep right and make well use of the mirrors. Also, on these segments, all other traffic tends to travel at relatively high speeds, at around 130-140 km/hr. In France and Belgium, speed limits seem to be obeyed most of the times.

4.1.4 *General observations from driver experiences*

1. In case the test driver was first in row at a traffic light, the driver kept the same pace and acceleration of the car next to the test car – whenever possible.
2. When cars travel ‘alone’, they tend to maintain a higher speed. Also, more high segment cars drive most of the times faster.
3. In some cases, drivers noticed that they were being followed. Most of the times, the drivers then decelerated. In these cases, the test driver aborted the following procedure and waited for a next car to follow.

4.2 Weather

The weather in general was modest, except for one German driving day which was rainy and foggy, influencing the driving behaviour significantly (lower driving speeds).

4.3 Trips

The trips were designed to give a coverage of all road types. This required start and stop in mid-size towns for sufficient urban distance. Moreover, the towns were selected to achieve more rural distance, as a random selection of 50 km trips often leads to large motorway distance.

4.3.1 the Netherlands

Netherlands 1	**Segment**	**Start**	**Start time**	**End**
13-5-2016	**1**	Naaldwijk	8:10	Stadhuis Leiden
vrijdag	**2**	Stadhuis Leiden	9:23	DekaMarkt Haarlem
	3	DekaMarkt Haarlem	10:16	Station Alkmaar
	4	Station Alkmaar	11:19	Aldi Hoorn
	5	Aldi Hoorn	12:28	Hogeschool van Amsterdam
	6	Hogeschool van Amsterdam	13:10	Almeerse Sportclub Waterwijk
	7	Almeerse Sportclub Waterwijk	14:25	Evangelische B.S. De Parel
	8	Evangelische B.S. De Parel	15:10	Plus Supermarkt
	9	Plus Supermarkt	16:04	Action Capelle a/d Ijssel
	10	Action Capelle a/d Ijssel	17:10	RDM Campus
	11	RDM Campus	17:52	Delft (DATA!)
Netherlands 2	**Segment**	**Start**		**End**
27-5-2016	**1**	Naaldwijk/Delft	7:56	Woerden
vrijdag	**2**	Woerden	9:00	Esso Amersfoort
	3	Esso Amersfoort	9:53	De Vijver, Zutphen
	4	De Vijver, Zutphen	11:05	Zwaaikom Hengelo
	5	Zwaaikom Hengelo	12:05	Grote kerk Enschede
	6	Grote kerk Enschede	?12:30	Rechtbank Almelo
	7	Rechtbank Almelo	13:34	Stadshart Zwolle
	8	Stadshart Zwolle	14:35	Bataviahaven Lelystad
	9	Bataviahaven Lelystad	15:34	Bijlmer, Amsterdam
	10	Bijlmer, Amsterdam	16:37	Oegstgeest Winkelcentrum LV
	11	Oegstgeest Winkelcentrum LV	17:37	Naaldwijk Dortlaan 4
Rit Alphen aan den Rijn		**Start**		**End**
29-5-2016	**1**	Naaldwijk (km 22101)	12:57	Honselersdijk
zondag	**2**	Honselersdijk (km 22105)	13:39	Alphen aan den Rijn
	3	Alphen (km 22152)	15:09	Den Haag (Mariahoeve)
	4	Den Haag (km 22214)	17:05	Naaldwijk

Netherlands 3				\
	Segment	**Start**		**End**
3-6-2016	**1**	Naaldwijk/Delft	7:52	SS Rotterdam
vrijdag	**2**	SS Rotterdam	8:47	Kasteel Bouvigne
	3	Kasteel Bouvigne	9:42	Heyhoefpromenade
	4	Heyhoefpromenade	10:15	Haverveld
	5	Haverveld	11:39	Café Oryent
	6	Café Oryent	12:42	Koffiecentrale
	7	Koffiecentrale	13:40	Ziekenhuis Venray
	8	Ziekenhuis Venray	14:22	Shell tankstation
	9	Shell tankstation	15:05	Haven Zaltbommel
	10	Haven Zaltbommel	15:53	Dillenburgplein, Ridderkerk
	11	Dillenburgplein, Ridderkerk	17:17	Delft
	12	Delft	17:56	Naaldwijk

4.3.2 Trips France

from	**Start time**	**To**	arrival
	18614 km		
Naaldwijk	7:58	Lille	11:18
Lille	11:40	Arras	13:10
Arras	13:25	Amiens	14:36
Amiens	15:08	Clermont	16:24
Clermont	16:42	Cergy	18:34
from		**To**	
	19103		
Cergy	7:50	Paris	9:54
Paris	10:10	Versailles	10:57
Versailles	11:15	Évry	11:59
Évry	12:06	Paris	13:14
Paris	13:22	Meaux	14:38
Meaux	15:07	Soissons	16:26
Soissons	16:36	Compiègne	
Compiègne		Noyon	
Noyon		Saint-Quentin	17:36
from		**To**	
19428			
Saint-Quentin	7:37	Péronne	8:14
Péronne	8:20	Albert	8:48
Albert	8:53	Amiens	9:40
Amiens	10:06	Doullens	10:42
Doullens	10:46	Arras	11:31
Arras	11:50	Lens	12:10
Lens	13:22	Lille	16:41
Lille		Delft (DATA)	

Segment	Start time	from	To	arrival
6-jun-16		km 23834		
1.1	7:11	Naaldwijk	Paris	12:57
1.2	13:07	Paris	Versailles	13:51
1.3	14:11	Versailles	Paris	15:34
1.4	15:41	Paris	Paris	17:19
Segment	**Start time**	**From**	**To**	
7-jun-16	24358			
2.1	7:30	Paris	Orly	8:47
2.2	8:47	Orly	Paris	10:03
2.3	±10:16	Paris	Argenteuil	11:14
2.4	11:18	Argenteuil	Paris	12:15
2.5	12:16	Paris	Naaldwijk	17:45

4.3.3 Germany

Segment	Start time	From	To	arrival
23-May-16	30-5-2016	KM 22233		
1.1	7:40	Naaldwijk	Arnhem	9:40
1.2	9:58	Arnhem	Emmerich am Rhein	10:53
1.3	10:59	Emmerich am Rhein	Wesel	11:43
1.4	11:59	Wesel	Duisburg	12:55
1.5	13:18	Duisburg	Kempen	14:03
1.6	14:23	Kempen	Mönchengladbach	14:59
1.7	15:06	Mönchengladbach	Rommerskirchen	15:56
1.8	16:03	Rommerskirchen	Köln	16:43
1.9	16:50	Köln	Bonn	17:54
Segment	**Start time**	**From**	**To**	
24-May-16	31-5-2016	km 22640		
2.1	7:52	Bonn	Köln	8:55
2.2	9:00	Köln	Bonn	10:00
2.3	10:22	Bonn	Flughafen Köln/Bonn	10:41
2.4	10:46	Flughafen Köln/Bonn	Wipperfürth	11:33
2.5	11:54	Wipperfürth	Schwelm	12:31
2.6	12:40	Schwelm	Essen	13:28
2.7	13:52	Essen	Mettmann	14:38
2.8	14:44	Mettmann	Düsseldorf	15:39
2.9	16:03	Düsseldorf	Mönchengladbach	16:57
2.10	17:01	Mönchengladbach	Neuss	17:41

Segment	Start time	From	To	
25-May-16	1-6-2016	KM 22948		
3.1	8:11	Neuss	Düsseldorf	8:54
3.2	9:04	Düsseldorf	Wuppertal	10:02
3.3	10:12	Wuppertal	Bochum	10:57
3.4	11:06	Bochum	Essen	11:50
3.5	12:09	Essen	Velbert	12:37
3.6	12:45	Velbert	Mettmann	13:03
3.7	13:06	Mettmann	Düsseldorf	13:44
3.8	14:03	Düsseldorf	Krefeld	
3.10		Krefeld	Duisburg	14:36
3.11	14:40	Duisburg	Delft	17:25
	17:54	Delft	Naaldwijk	18:24

4.3.4 Belgium

Segment	Start time	From	To	arrival
23-May-16				
1.1	7:27	Naaldwijk (20277 km)	Delft	8:10
1.2	8:23	Delft	Antwerpen	10:39
1.3	10:52	Antwerpen	Dendermonde	12:15
1.4	12:29	Dendermonde	Gent	
1.5		Gent	Aalst	12:57
1.6	13:00	Aalst	Brussel	13:52
1.7		Brussel	Zaventem	
1.8		Zaventem	Brussel	15:05
1.9	15:30	Brussel	Leuven	16:18
1.10	16:39	Leuven	Ottignies-Louvain-la-Neuve	17:12
1.11	17:16	Ottignies-Louvain-la-Neuve	Namen	18:00
Segment	**Start time**	**From**	**To**	
24-May-16				
2.1	7:34	Namen	Marche-en-Famenne	8:09
2.2	8:18	Marche-en-Famenne	Bastenaken (Bastogne)	8:53
2.3	9:01	Bastenaken (Bastogne)	Aarlen (Arlon)	9:40
2.4	9:50	Aarlen (Arlon)	Luxemburg	10:30
2.5	10:48	Luxemburg	Saeul	11:15
2.6	11:25	Saeul	Bastenaken (Bastogne)	12:18
2.7	? 12:24	Bastenaken (Bastogne)	Marche-en-Famenne	13:22
2.8	13:56	Marche-en-Famenne	Luik (Liege)	14:49
2.9	14:57	Luik (Liege)	Sint-Truiden	16:05
2.10	16:09	Sint-Truiden	Namen	17:07

Segment	**Start time**	**From**	**To**	
25-May-16				
3.1	7:27	Namen	Luik (Liege)	8:37
3.2	8:43	Luik (Liege)	Hasselt	9:31
3.3	9:36	Hasselt	Peer	10:08
3.4	10:17	Peer	Geel	11:03
3.5	11:13	Geel	Aarschot	11:52
3.6	11:57	Aarschot	Leuven	12:22
3.7	12:37	Leuven	Brussel	13:11
3.8	13:47	Brussel	Dendermonde	14:53
3.9	14:56	Dendermonde	Sint-Niklaas	15:18
3.10	15:29	Sint-Niklaas	Antwerpen	16:22
3.11	16:33	Antwerpen	Delft	18:06

5 Results per country

For each of the countries and each of the trips the $v*a_{pos}$(95%) and RPA were determined. The $v*a_{pos}$(95%) results were submitted to the RDE-LDV meeting of 16 June 2016.

5.1 The $v*a_{pos}$(95%) results

Below the results of each country is plotted separately. These results were shared with the stakeholders in June 2016.

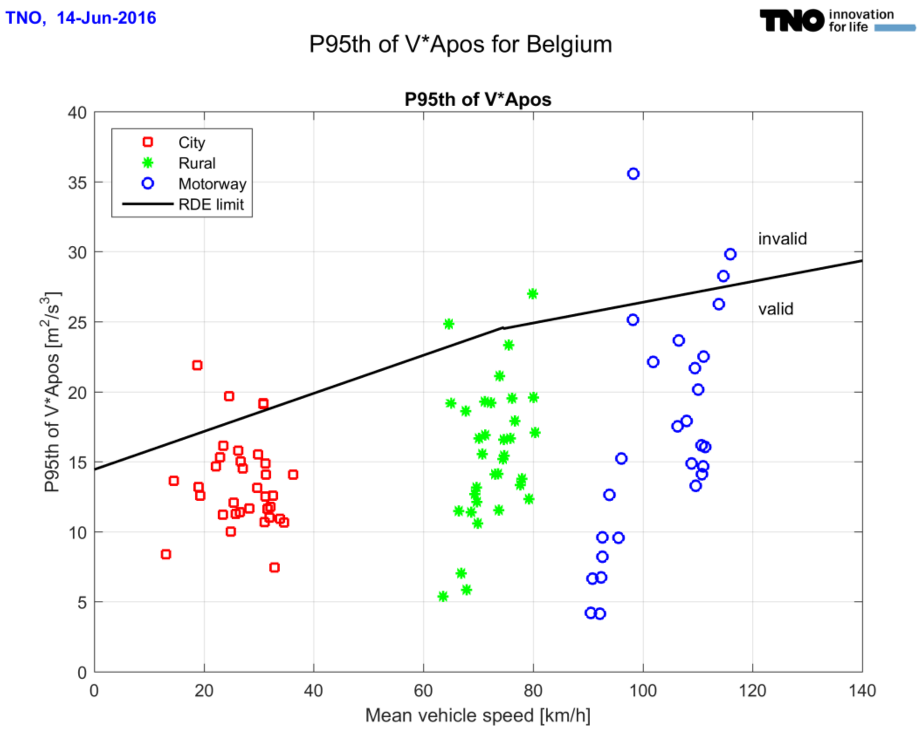

Figure 2: The results of the car chase tests in Belgium.

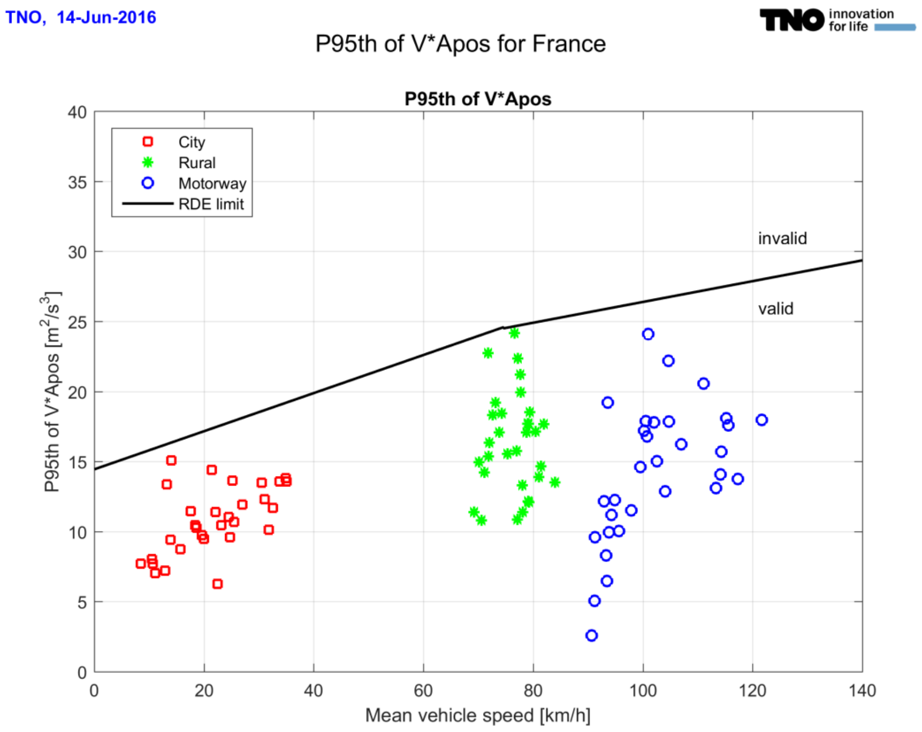

Figure 3: The results of the car chase tests in France.

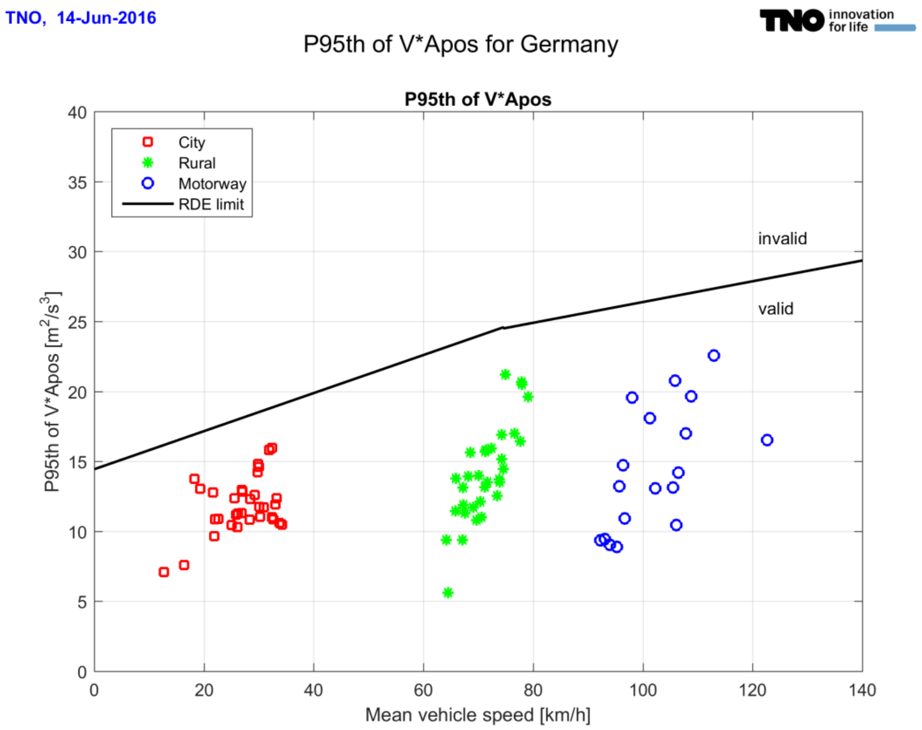

Figure 4: The results of the car chase test in Germany.

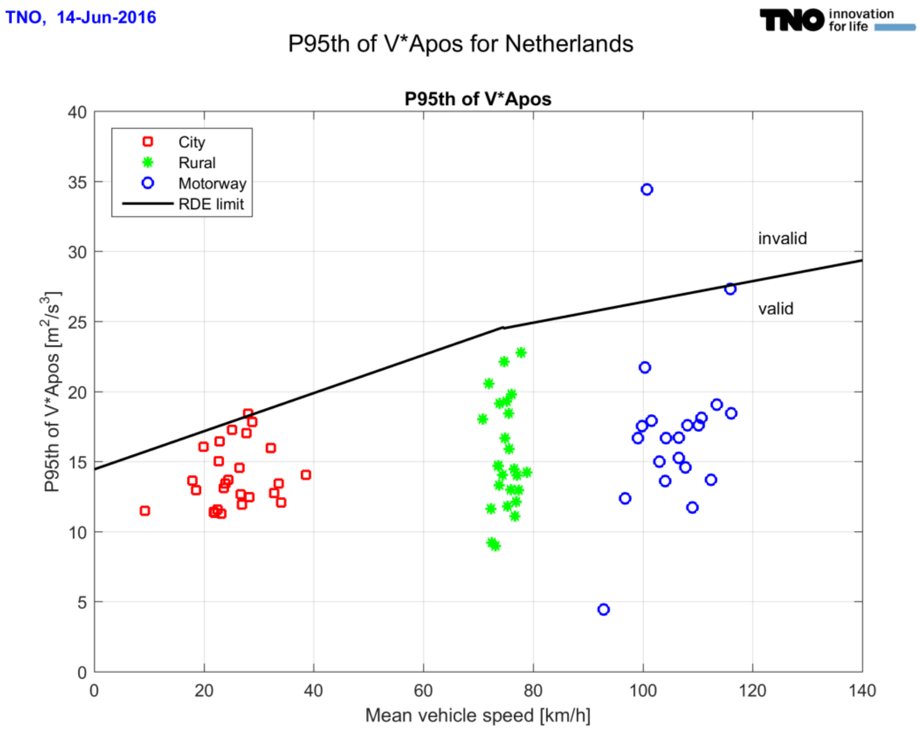

Figure 5: the results of the car chase tests in Germany

5.2 The RPA results

Belgium not only has the most trips that failed the v*a_{pos}(95%) criteria, it also has the most trips that failed the RPA criteria. Clearly, the driving in Belgium is rather dynamic with a wide span in driving behaviour. Very likely it is linked to the infrastructure and city planning as well. Another explanation is the being stuck behind slow trucks on rural roads, as was the experience of the test driver in Belgium.

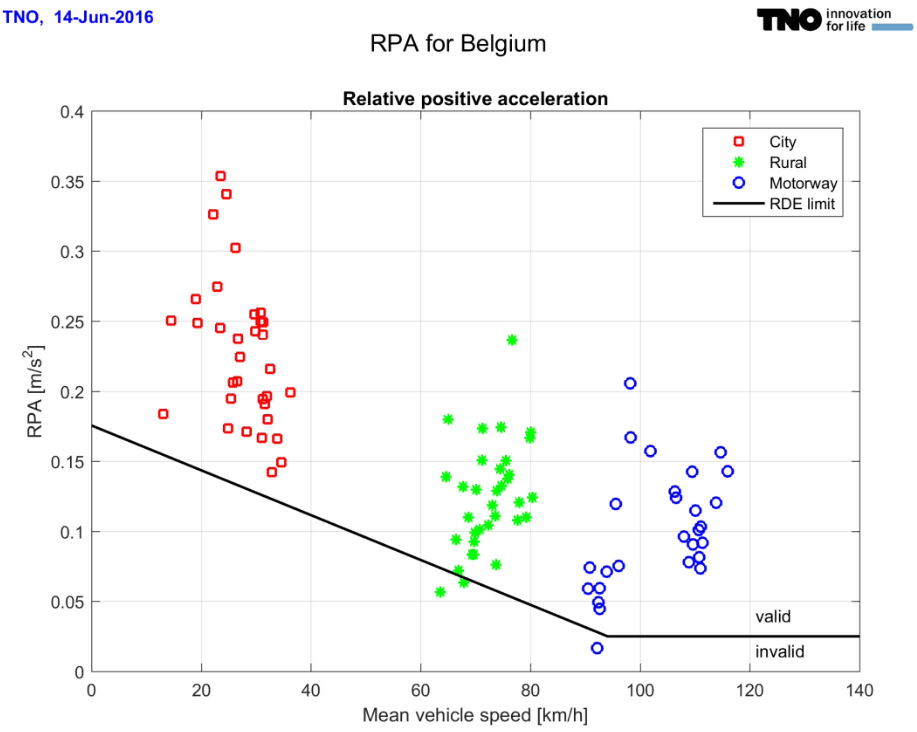

Figure 6: The RPA lower bound for RDE, compared against the chase car tests in Belgium.

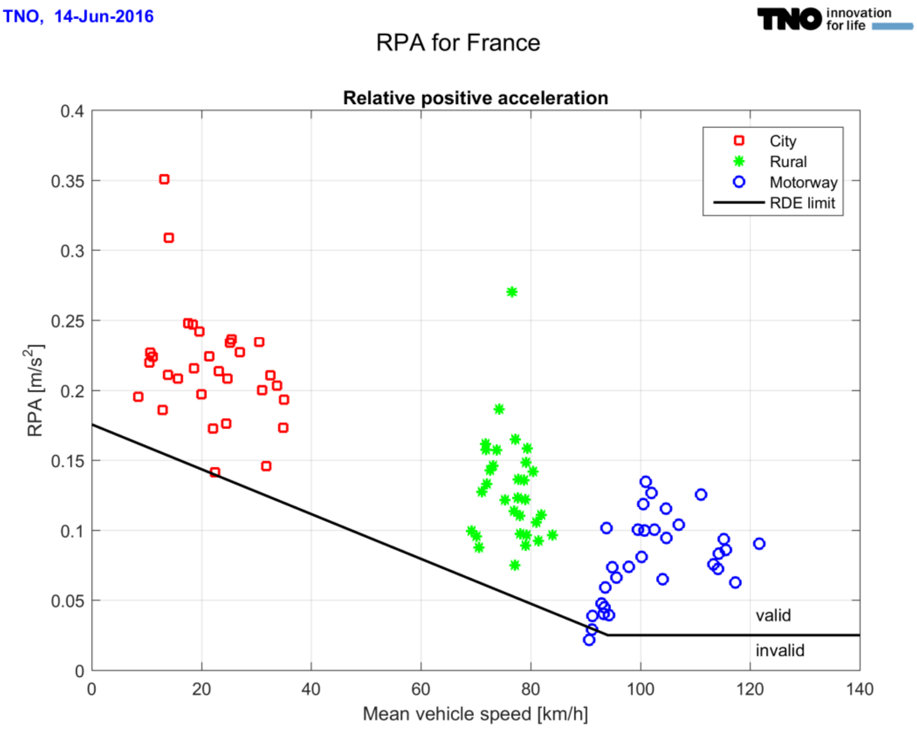

Figure 7: The RPA value for the chase car tests in France.

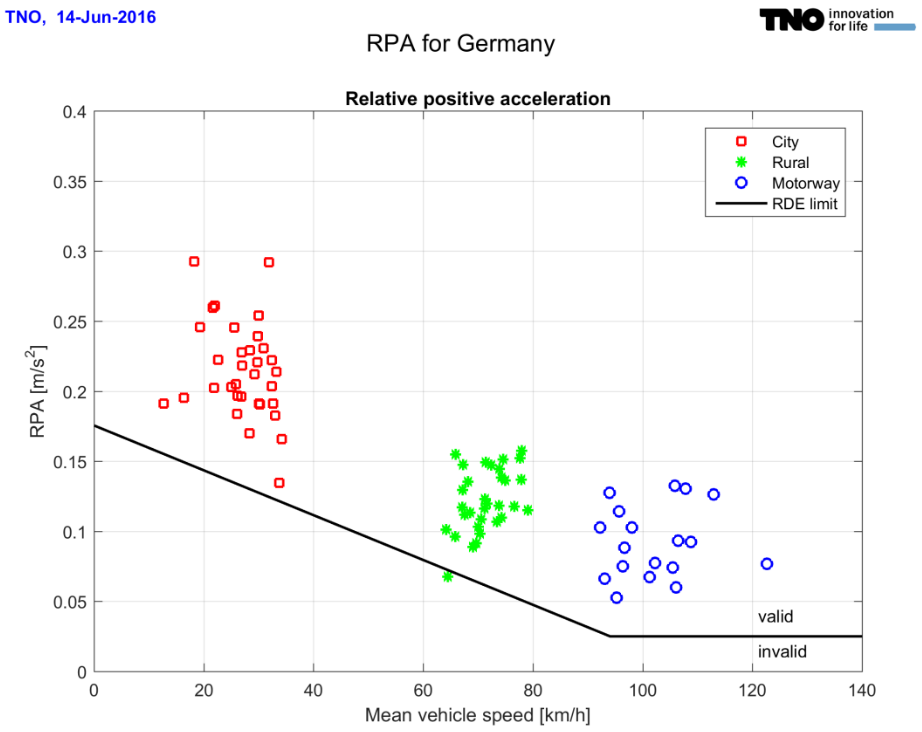

Figure 8: The RPA values of the trips in Germany.

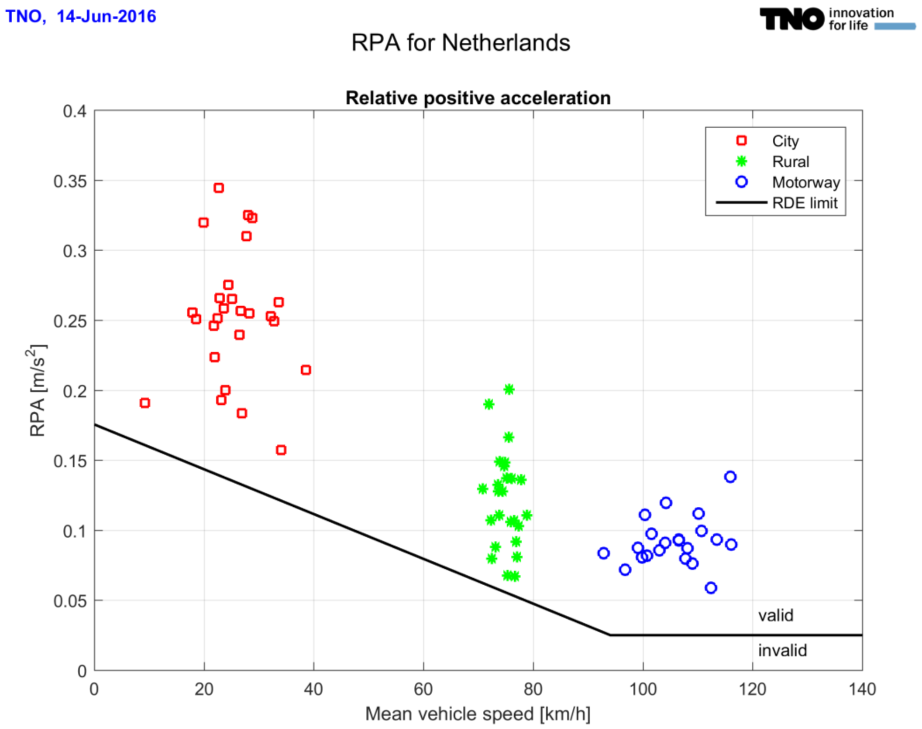

Figure 9: The RPA values of the chase car trips in the Netherlands.

5.3 Observations on driving dynamics

The trips revealed that no average driving exists; a broad range of driving behaviours has been observed. In order to sufficiently cover 'normal' driving behaviour, RDE boundaries should allow for inclusion of this broad range. Driving dynamics vary significantly among countries. The highest dynamics have been observed in Belgium. A significant number of Belgian trips was well above the v*apos(95%) limit value. The average speed during urban driving was frequently below the lower limit of 15 km/h, most strikingly demonstrated in the Paris trips. This stop and go traffic is frequently observed in densely populated areas with high traffic density; typically situations with exceedances of NO_2 concentrations. Higher (or absence of) speed limits in a county are not necessarily reflected in high dynamics, as is the case for Germany.
If the v*apos(95%) limit was set at a higher value, a wider range of driving behaviour throughout Europe, in particular in Belgium, would be covered. If the 15 km/h minimum average speed during urban driving of RDE trips was lowered, a wider range of stop and go traffic in densely populated urban areas, in particular observed in France, would be covered. The large national differences observed are expected to be due to a combination of the national temperament, the road infrastructure, the level of congestion, and the enforcement of traffic regulation.

In general, for daytime driving, the RPA limit for tame driving is not met. In principle, this limit seems a reasonable boundary to excluded extreme trips and driving behaviour on the tame side.

6 Impact of power-to-mass ratio on driving behaviour

Driving behaviour during a trip is affected by many aspects. The infrastructure and congestion play an important role. A red traffic light will force a stop, and a vehicle in front will limit the freedom of the driver to accelerate. From country to country there are differences, as noted in the previous chapters, that will affect the driving behaviour. However, the personal freedom of the driver to drive more sportive, or moderate, is another factor in the driving behaviour. It can be argued the personal style is limited on the one hand by the traffic rules and on the other hand the capabilities of the vehicle. However, RDE legislation is developed mainly on the premise that the driving behaviour is not affected by the power-to-mass ratio, or capabilities, of the vehicle. On the basis of this premise the RDE driving behaviour boundaries are uniform for all vehicles: vehicles are not tested within their capabilities, but within a smaller subset of driving behaviour related to the notion of the normal or average driving.

The premise if all vehicles are driven the same, despite large differences in engine power is investigated in this chapter. In the car chase testing, the rated power and vehicle weight has to be recovered from scanning the license plates. This has been rather difficult. Therefore only limited data was obtained and results are only indicative. Another source of information was a test program with vans with a large range in power to mass ratios, from the different payloads used.

$V*a_{pos}$ has a direct relation to the power-to-mass ratio of the vehicle. The engine has a certain power to accelerate. If an engine has rated power of 80 kW (a value typical for modern cars), this power is available at a high engine speed. In normal driving the engine speed is lower, and typically about 50 kW remains to be used to propel the vehicle. At low velocity, say 36 km/h or 10 m/s, the force needed to overcome resistance is about 200 Newton. Therefore, 2 kW is needed to overcome resistance and 48 kW remains to accelerate. Given a vehicle weight of 1400 kg, it means the maximal attainable $v*a_{pos}$ in normal driving for a 80 kW vehicle is $v*a = 34\ m^2/s^3$. At higher velocity, say 108 km/h, or 20 m/s, the resistance is about 500 Newton, which require 15 kW engine power, which leaves an available power of 35 kW. This gives a maximum $v*a = 25\ m^2/s^3$. If people drive in a lower gear, they have more power available, and the maximal attainable values are higher.

6.1 Licence plates scan in the Netherlands

In the Dutch part of the test program, a camera was installed on the dashboard which collected license plate information of the cars in front. This process was a bit cumbersome, and the camera did not always point in the right direction. Still, a large number of license plates were recognized. For the Netherlands about 500 license plates were in front of the chase car for longer than 10 seconds and were considered to be a vehicle that was followed. If the power-to-mass ratio is separated in three more or less equal groups: low powered, medium powered, and high powered, enough data remains to make a distribution of the v*a values for each group.

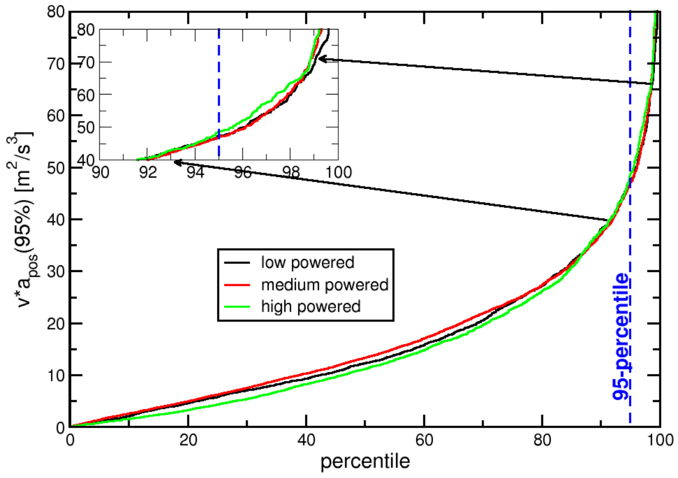

Figure 10: The observed sorted distribution of v*a_{pos} values combined with the license plate vehicle identification. Only minor effects for high-powered vehicles are observed, as can be seen from the inset with values close to the limit.

The high powered vehicles show only a minor increase in the high v*a values at the cost of less of lower v*a values. The results for which camera information is available seems somewhat biased towards the straight-stretch road data, i.e., rural roads and motorways. Hence, the observed values are high compared to the full dataset. Upon closer examination, at about 92%-93% the. the green line for high powered vehicles, in Figure 10, crosses the other lines. At lower percentiles (to the left of the crossover) high powered vehicles have relatively lower v*a_{pos} values and at higher percentiles (to the right of the crossover) the v*a_{pos} values are relatively higher. The existence of such a crossover is not surprising. In many cases the average velocity of vehicles are restricted by the traffic flow they are part of. The remaining freedom is harder acceleration to reach the cruise velocity more quickly. This results in fewer samples at lower accelerations.

The limited amount of data, of about half an hour each for the three vehicle segments, restricts the conclusions from this test. A minor effect is observed for different power-to-mass vehicles, but it is not significant at the scales under consideration.
Nevertheless, the analyses underpin the importance of the introduction of the 95% percentile assessment in the RDE legislation. It mitigates (possible) differences in driving behaviour between power classes. To further improve an equal treatment of different power classes a further reduction to 92% could be considered.

6.2 Light Commercial Vehicles (N1)

The assumption, underlying the RDE legislation, that driving behaviour is not affected by the power-to-mass ratio of the vehicle is even more strained for light-duty N1 vehicles, meant for carrying goods. Passenger cars have typical power-to-mass ratios of 45 kW/ton and up, to extremely high values, while larger vans usually have a lower power-to-mass ratio, which is further reduced if the vehicle is fully laden.

Therefore, the aggressive driving limit in RDE legislation has no bearing on the driving behaviour with vans. In order to assess the typical $v*a_{pos}(95\%)$ of vans with partial payload and full payload, the TNO test data[5] for Euro-5 LCV's was revisited. Ten vans were driven on road in a reference trip, similar to a RDE trip with both partial (28%) and full (100%) load. All vehicles were driven by test drivers with the instruction to drive moderate to normal, and a few additional tests were executed with an aggressive, or sporty, driving style.

From these tests the $v*a_{pos}(95\%)$ and the RPA were determined. The values for $v*a_{pos}(95\%)$ were all much lower than the RDE limit. It turns out that there is a clear relation between the power-to-mass ratio of the vehicles and the $v*a_{pos}(95\%)$ driving behaviour parameter. The results of $v*a_{pos}(95\%)$ are plotted against the power-to-mass of the test vehicle, for the two different payloads. Half of power-to-mass in [kW/ton] is an apparent upper limit, also for the sportive trips, indicated by "S" in the plots. The 50% rule of power available for acceleration is in line with physical principles. Power-to-mass and $v*a_{pos}(95\%)$ have the same units of [m^2/s^3]. If the number of transients, i.e., changing from one distinct velocity to another, is small compared to amount of driving at constant, or the excess power is not used, the $v*a_{pos}(95\%)$ can be substantially lower than half the rated power. But for low-powered vehicles, which require substantial time already to reach the target velocity, full power is quite common. This is not to be classified as aggressive driving.

[5] TNO Report 10192, On-road NOx and CO2 investigations of Euro 5 Light Commercial Vehicles, Gerrit Kadijk, Norbert Ligterink, and Jordy Spreen (2015). TNO R10356, NOx emissions of Euro 5 diesel vans – test results in the lab and on the road, Gerrit Kadijk, Norbert Ligterink, Pim van Mensch, and Richard Smokers (2016).

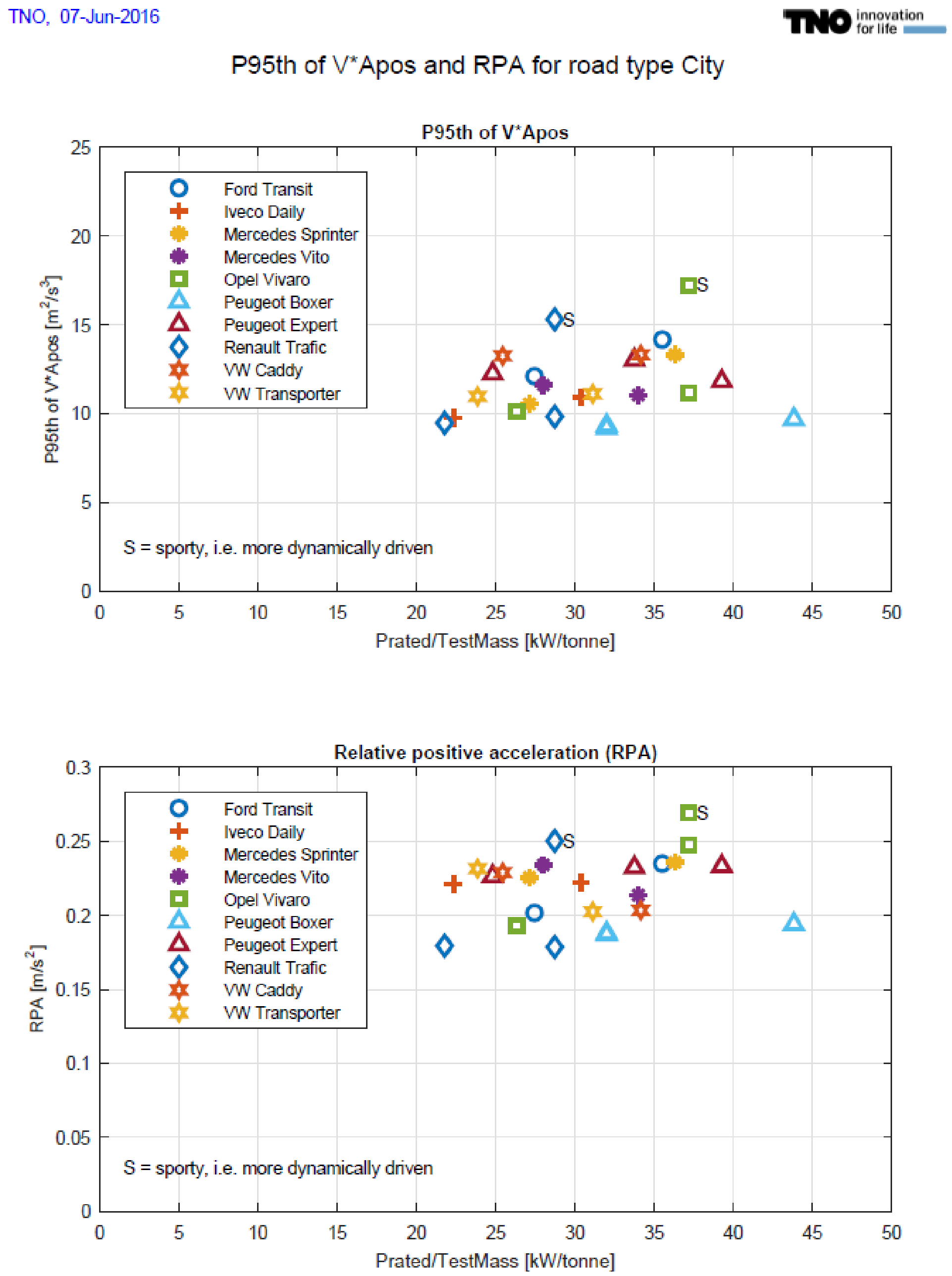

Figure 11: The v^*a_{pos}(95%) and the RPA values for the urban velocity bin of the reference trips of all vans.

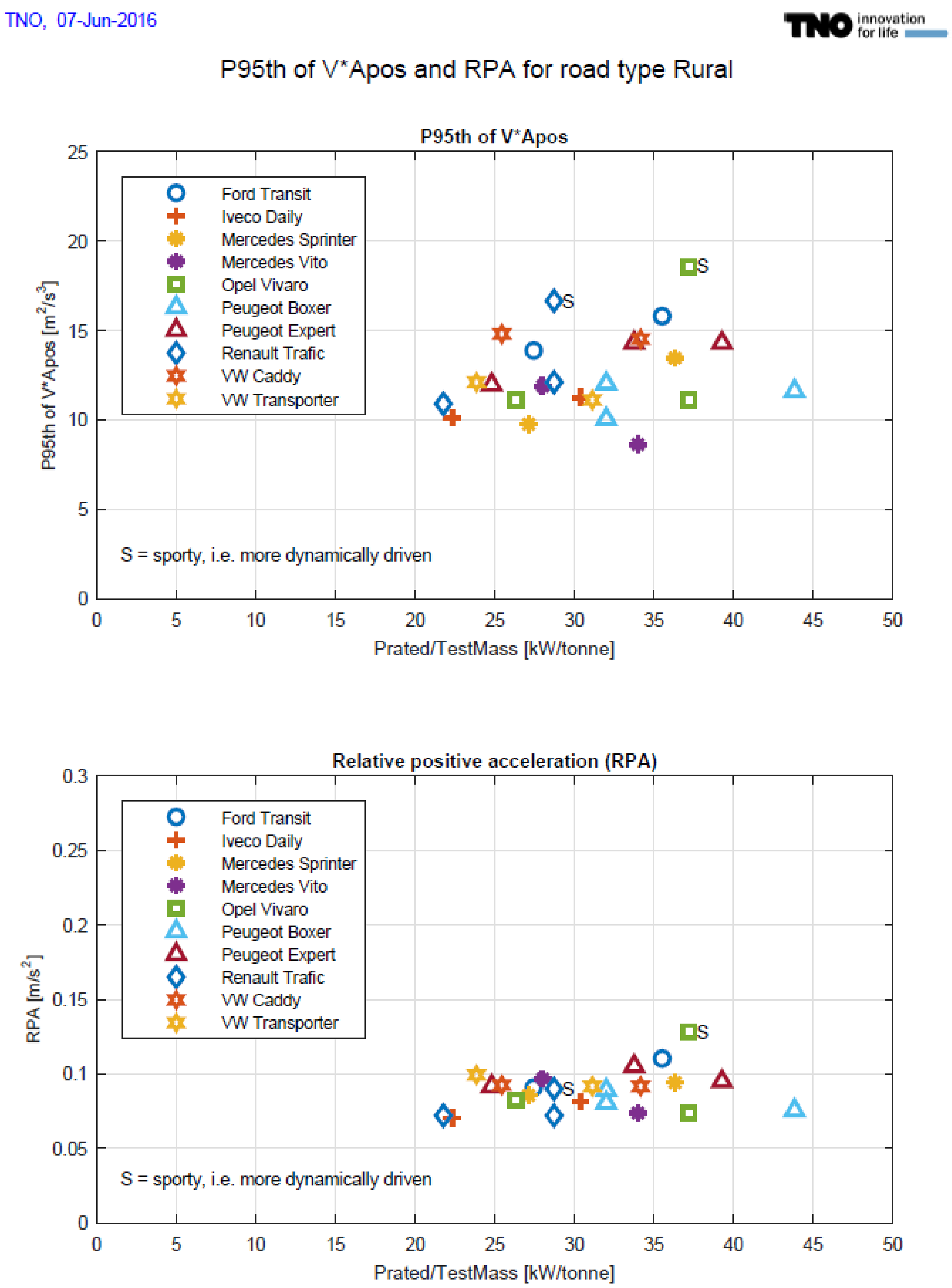

Figure 12: The v*a_{pos}(95%) and the RPA of the rural part for all vans.

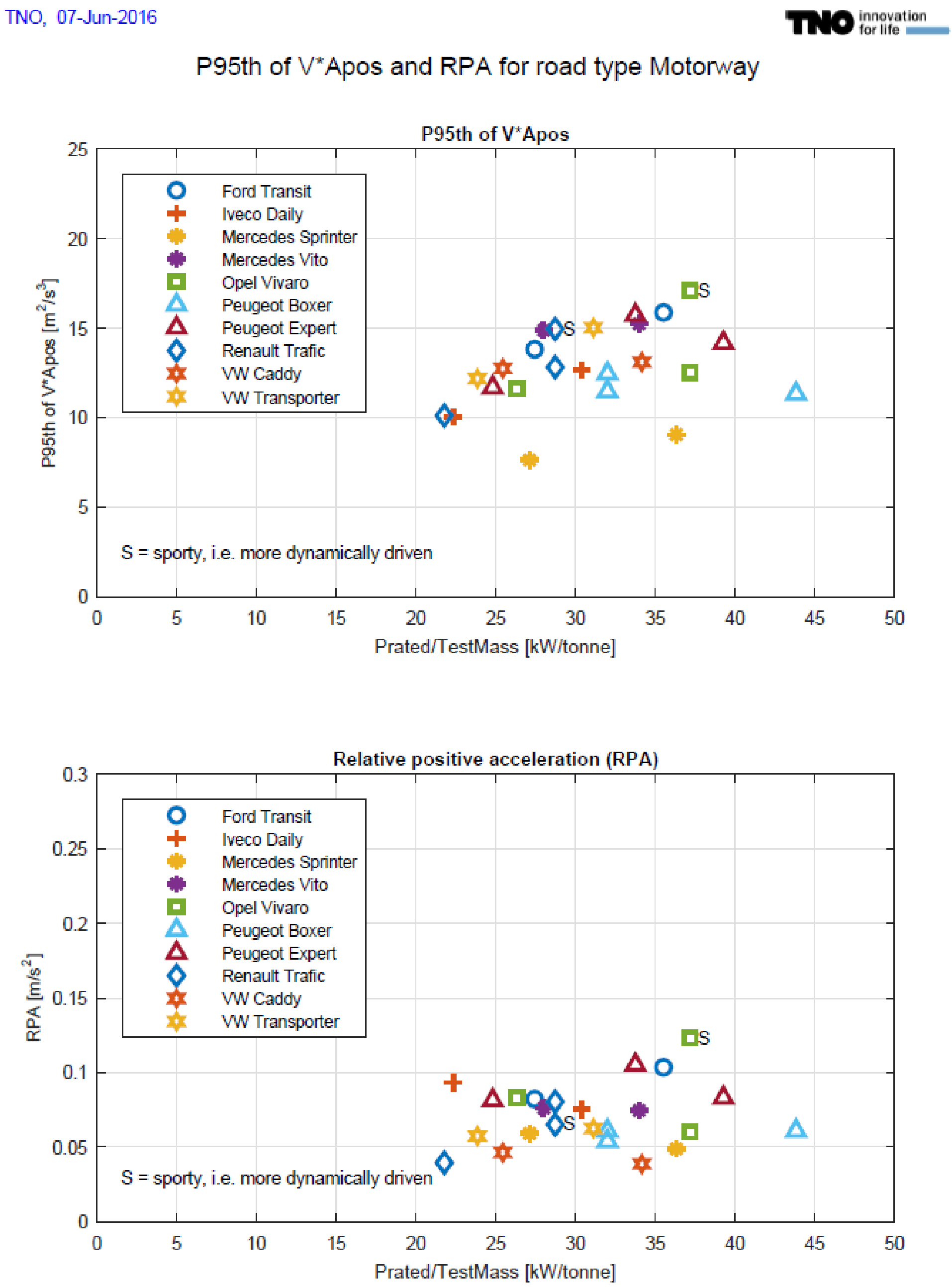

Figure 13: The v*apos(95%) and the RPA of the motorway part.

7 Radar test of bias introduced by the test driver

A radar is ideally suited to determine the relative velocity of the car in front, compared to the chase car. As the the velocity of the chase car is measured accurately, from the radar signal the actual velocity of the car followed can also be determined accurately. By comparing the driving behaviour derived from both the chase car data set and the followed car data set, any bias introduced by the driver can be determined.

The installed radar was able to track up to 40 objects within the range of 1-200 metres in front of the vehicle. This generated a lot of data, with a lot of different objects irrelevant to the study. A typical snapshot, as shown in Figure 14, gives a busy picture of stationary objects, vehicles from multiple lanes and vehicles further up the road.

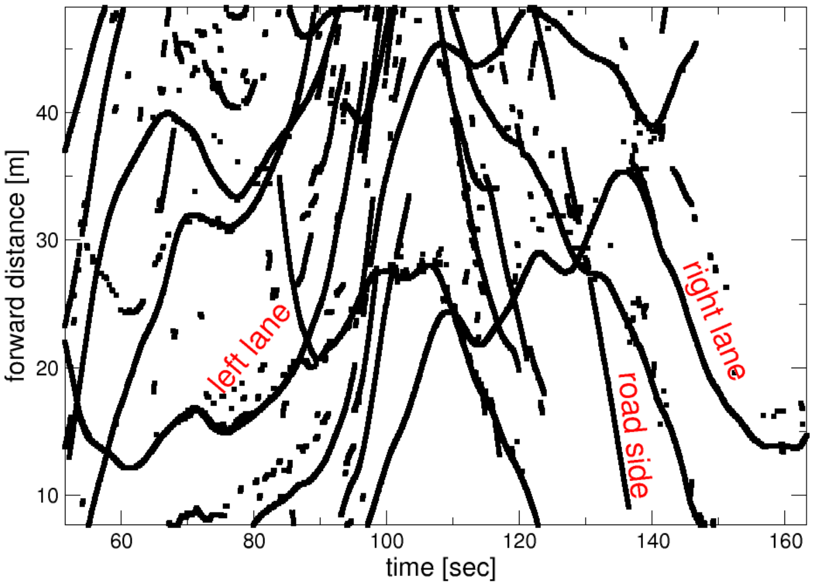

Figure 14: Typical picture of the raw radar data. Increaseing distances means the object is moving faster. Decreasing distances means the objects move slower. Some stationary objects, like street lights and traffic signs, are also picked up as fast approaching objects.

The signal is generally quite clear and the objects are delivered with a rate of about 5 kHz for separate objects. Its results in a full scan, of all objects, at a rate of about 100 Hz. To remove noise, these results are down-sampled to about 10 Hz. The vehicle in front is identified on the basis of the shortest frontal distance where the longitudinal distance counts ten times as high as the lateral distance. Vehicles in the next lane are about 2.5 metres to the side and close in front, such that a vehicle 50 metres direct in front has the same distance as a car passing by in the next lane. This implies that cars in front can be distinguished from cars passing by as long as the test driver limits the distance between chase car and the car in front to 50 meters. The cars passing by, or passed by, are excluded also on the basis of the larger relative velocity. The signal with a combination of a small forward distance and a small relative velocity is designated as the car in front. This leads to a high recognition of unique vehicle for longer periods. Of the selected object information is available of the relative velocity and longitudinal and lateral distance to the test vehicle. The data combined yields a complete picture of the relative position of the two vehicles over time. See Figure 15 for a typical example, during acceleration where both the velocity and the distance increases.

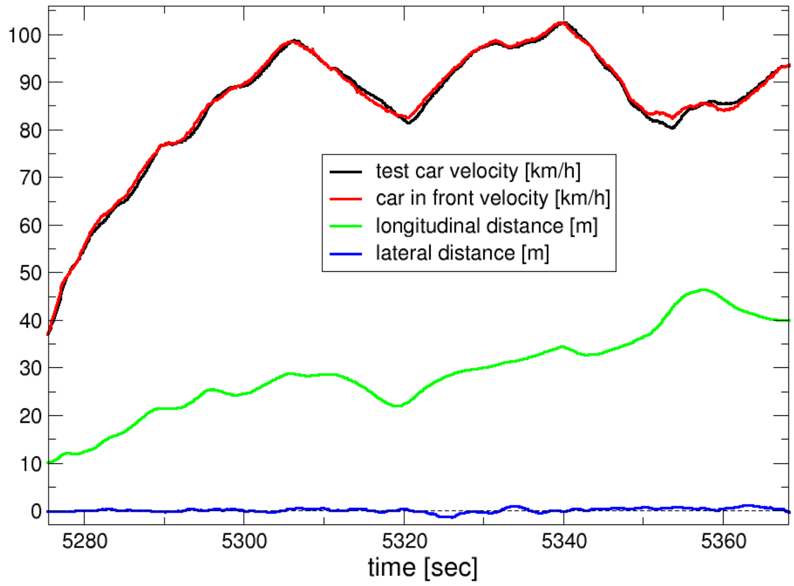

Figure 15: A typical example of the 10 Hz raw velocity signals of the two cars: the ABS signal of the test car, and the sum of the test car and the relative radar velocity for the car in front. Typically, the chase car has a delay of about a second in the velocity changes.

At lower velocities the typical distance is about 10 metres, which increases to about 50 metres at the highest velocities on the motorway. During the programme the test driver has decreased the distance somewhat to avoid other vehicles cutting in between.

Essential to the soundness of the car chase method is the magnitude of acceleration of the test car compared with the car in front. Since $v*a_{pos}(95\%)$ is the key measure, this value of both cars are compared for all the trips. Some data must be excluded from this analysis, in between two different cars followed. The correlation of $v*a_{pos}(95\%)$ of both cars is a stringent test, as it is already a measure of the more extreme parts in the total driving. Any bias would directly emerge in this 95% percentile value. In Figure 16 the results are shown. The car in front exhibits a slightly higher $v*a_{pos}(95\%)$ on average than the chase car. In part this may due to the radar signal. Excluding less transitional data, from switching cars, increases the difference between the chase car and the cars in front. It can be concluded both signals have similar degrees of aggressive behaviour. The spread in the correlation is rather large. It is expected that in part this is due to the data processing and combination of the in-vehicle and radar signals. This will be investigated further.

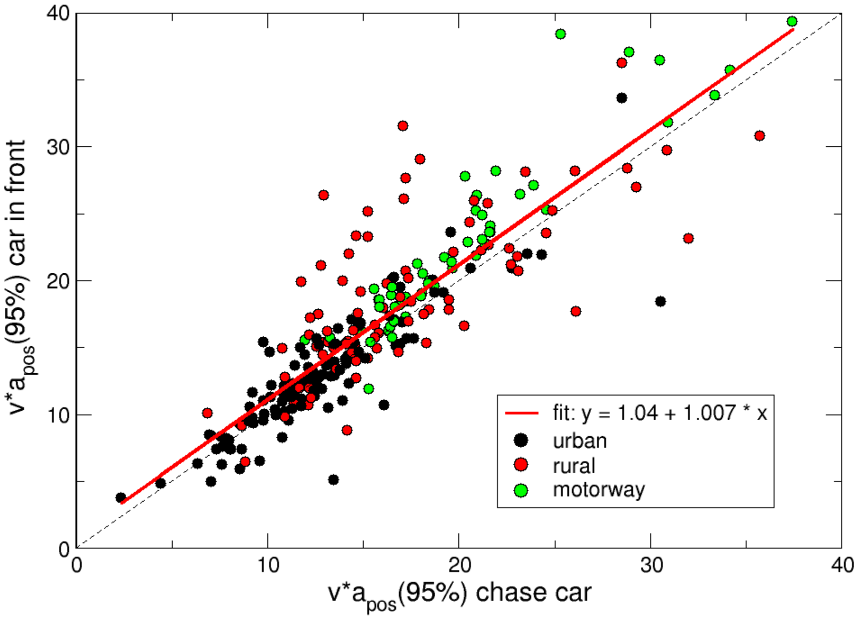

Figure 16: The correlation between the velocity of the chase car and the velocity of the car in front as observed by the radar. Velocity data during transitions between cars to follow is excluded.

On average the driving behaviour of both cars is very similar. If the test car introduces some bias, it is slightly more towards lower dynamics rather than higher dynamics. This is not a general result, but specific for this driver and this test program. The fact that the test car is a high-powered vehicle with automatic transmission may also have helped the test driver to focus on the car in front. Hence some concerns remain on the normal driving behaviour with respect to the RDE boundary. However, this is a minor issue compared to the observed variation from country to country.

This car chase project performed by TNO underestimates of real world dynamics across different countries and the results of a previous, similar project have been used to establish a compromise decision on the driving behaviour boundaries in RDE legislation. In this respect a part of normal European driving might be excluded from the RDE assessment. In particular, given that $v^*a_{pos}(95\%)$ is related to the power demand from the engine, a boundary that excludes a part of driving behaviour may lead to emission control optimization limited to part of the full span of European driving behaviour. A higher limit value for the $v^*a_{pos}(95\%)$ boundary of aggressive driving would deliver a safeguard.

8 Conclusions

The 2016 project demonstrates the validity to use results generated in a well-designed car chase campaign to determine real world driving behaviour. The results confirm that a right decision was taken to increase the $v*a_{pos}$(95%) limit value for aggressive driving in the negotiation of the 2nd RDE package. Even though the decision was based on 2015 information of driving behaviour in The Netherlands, by no means Dutch driving behaviour is more dynamic than driving behaviour observed in neighbouring countries. In general the current RDE driving behaviour boundaries sufficiently cover normal driving behaviour, with the exemption of the high dynamics encountered in Belgium.

From the current study it can be concluded that the driving behaviour limits, as set in the RDE legislation are somewhat restrictive with respect to the normal use of a mid-range powered vehicle in different countries.

High powered vehicles show higher dynamics, expressed as $v*a_{pos}$, at higher $v*a_{pos}$ values, but less dynamics at lower $v*a_{pos}$ values. Between 90% and 95% percentiles of $v*a_{pos}$ values, there is a crossover where all vehicle classes, independent of their engine power show similar dynamics, This underpins the importance that the assessment of validity of RDE trips is performed at the 95% percentile of $v*a_{pos}$ values. A assessment at the 92% percentile would even be more adequate.

By no means the $v*a_{pos}$(95%) assessment is suited to prevent normally powered light duty vans from being tested at excessive aggressive driving during RDE tests. An assessment based on a power-to-mass limit would be preferable.

Even though the car chase approach is appropriate to determine real world driving behaviour, results from the TNO project tend to give a slight underestimation of driving dynamics. If the aim is to cover normal European driving behaviour to the largest possible extent in the RDE assessment, a higher limit value of $v*a_{pos}$(95%) could be considered.

9 Signature

The Hague, 31 March 2017 TNO

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