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Driving behaviour parameters for emission factors of heavy-duty vehicles

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Contents

1 Introduction

Emission factors of vehicles, used for air-quality assessments and emission inventories, are the average emissions for given traffic situations. The driving behaviour in these traffic situations is just as important for the emission estimates, as the emission characteristics of the vehicles. This report determines the current driving behaviour of heavy-duty trucks on different road types and congestion levels. The last update of heavy-duty driving behaviour stems from more than 10 years ago. Given the change in typical power-to-mass ratio and traffic situations on the road, the Pollutant Release and Transfer Register requested an update of driving behaviour. Furthermore, the driving behaviour in traffic situations with congestion were never properly investigated, despite the relevance for emissions of heavy-duty vehicles with modern emission control like SCR systems. This study provides this information in detail for the first time.

Emission measurements are translated to the standard traffic situations with the emission model. In practice, the measurement data of emissions per kilometre for specific vehicles is extrapolated to specified average driving behaviour, as defined by instantaneous velocity and acceleration. The number of vehicles, and the distance they cover per year, are important to make a reliable extrapolation for the overall emissions. This study determines the underlying average driving behaviour, for the defined traffic situations, like road type, speed limit and average velocity, from the real on-road driving collected in the last years.

For heavy-duty vehicles, the last update of the driving behaviour parameters took place in 2006. The update was based on a small, representative dataset with limited coverage of congestion circumstances. Besides the possibility that, due to changes in personal driving styles or traffic conditions, the typical driving behaviour might have changed over the past 10 years, the increase in power-to-mass ratio of heavy-duty vehicles might have influenced real-world driving behaviour as well. The new VERSIT+ emission model no longer has the restriction on the amount of driving data; all relevant driving data is included in the update.

Also, the emission behaviour of new Euro VI heavy-duty vehicles justifies an update of the driving behaviour parameters. Euro VI trucks have on average low NO_x emissions, but under some circumstances the NO_x emissions are exceptionally high. For example, at low velocities (<20 km/h) in urban areas and in congestion on the motorway, the SCR (Selective Catalyst Reduction) temperature is too low for optimal functioning. For Euro V trucks, this effect is expected to take place up to even higher velocities (<60 km/h). Euro IV trucks and older did typically not show this type of emission behaviour.

This study was carried out for the Pollutant Release and Transfer Register, which reports emissions in the Netherlands. A first update of the driving behaviour parameters is reported, using the truck and bus monitoring data from emission measurements performed by TNO that was available in 2017. Future updates may follow, as more monitoring data are being collected that better cover the wide range of driving conditions and heavy-duty vehicle types.

Moreover, the events of high emissions of Euro VI vehicles is likely linked to other aspects of driving behaviour than velocity and acceleration. In a future update, the duration of low-velocity driving may play a role.

2 Method to quantify driving behaviour

Emissions typically increase with both acceleration and velocity. To account for this variation, which depends on driving behaviour, a hot map is defined using acceleration and velocity, and different emissions are assigned to different areas. The areas in the map are typically labelled 1 (idling) until 10 (high velocity and high acceleration). The emissions are expressed as a vector **u** over different velocity/acceleration areas, and, likewise, the driving behaviour is expressed as a vector **q**. This vector **q** is simply the amount of time (in seconds) spent in each of the hot-map areas. The total emissions over a certain amount of time can then be calculated as:

$$EM\,[g] = \mathbf{q}[s] \cdot \mathbf{u}[g/s] = q1{*}u1 + q2{*}u2 + ... + q9{*}u9 + q10{*}u10.$$

This procedure is performed separately for different driving circumstances and road types. Both **q** and **u** must then apply only to specific driving circumstances, by selecting only input data (emission and driving behaviour) corresponding to certain road types, speed limits or average velocities. More information on the methodology for determining emission factors can be found in (Spreen et al., 2016).

The categories of driving circumstances used to define Dutch emission factors, are called SRM (Standaard Rekenmethode) categories. They are also used for the national emission inventory (Pollutant Release and Transfer Register: PRTR), and cover urban, rural and motorway driving, and different levels of congestion. Table 1 provides more detail on the definition of those categories in terms of vehicle velocity, road types and speed limits. The monitoring input data used to determine the new driving behaviour parameters in this study are accordingly divided into the seven SRM categories that apply for heavy-duty vehicles. Chapter 3 provides more detail on different possibilities to make this division.

Table 1 PRTR/SRM road category definitions. The grey lines only apply for light-duty vehicles.

SRM category	Description
WT1	**Urban average (v_{avg} <50 km/h)**
WS1	Urban congested (v_{avg} <20 km/h)
WM1	Urban normal (v_{avg} 20-30 km/h)
WF1	Urban free-flow (v_{avg} >30 km/h)
WT2	**Rural (v_{avg} 50-70 km/h)**
W80MSH (W83)	Motorway 80 km/h limit
WS3	Motorway congested (v < 50km/h)
WT3	**Motorway average (v_{avg} >70 km/h)**
W100MSH (W03)	Motorway v<100 km/h, 100 km/h limit
W100ZSH (W13)	Motorway 100 km/h limit
W120ZSH (W23)	Motorway 120 km/h limit
W130 (W33)	Motorway 130 km/h limit

Once all data is assigned to the specific driving circumstances, the **q**-vectors can be determined. To this end, the velocity and mid-point acceleration of each second of the 1Hz timeseries data is determined per vehicle. The combination of velocity and acceleration determines to which hot map area, from q1 until q10, this second should be assigned. Counting the time spent in each of the areas determines a **q**-vector per vehicle, under the selected driving circumstances.
Figure 2-1 until Figure 2-3 show the distribution of velocity and acceleration on urban, rural and motorway roads, respectively. The colours in the graphs represent the time count in each bin, similar to the **q**-vector count, albeit with a much higher v-a bin resolution.

To avoid a bias in the data of vehicles that have been monitored for a longer time, the **q**-vector is first determined per vehicle. Only then, the results are averaged, such that each vehicle has the same contribution independent of the number of hours of data available. It should be noted that the acceleration of trucks seldom exceeds 1 m/s^2. Given a power-to-mass ratio of 25 kW/ton, the acceleration is physically limited to 1 m/s^2 at about 70 km/h. The higher the velocity, the lower the accelerations. Passenger cars typically have acceleration capabilities that are a factor 3 higher than those of trucks.

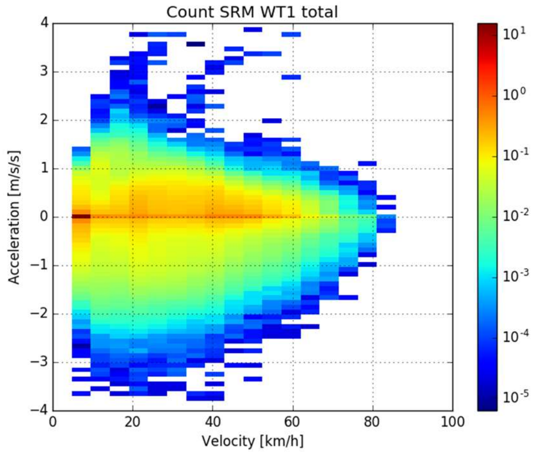

Figure 2-1 Velocity-acceleration distribution of trucks on urban roads (WT1).

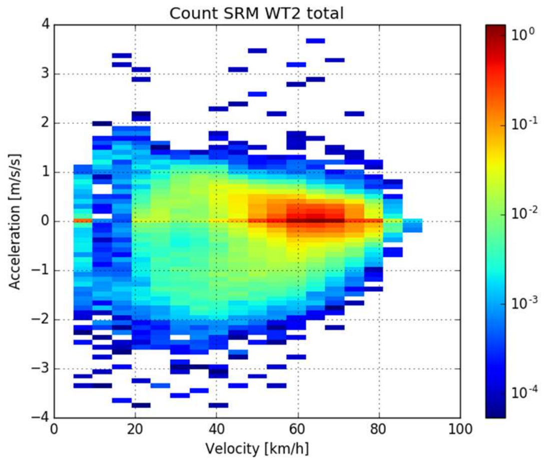

Figure 2-2 Velocity-acceleration distribution of trucks on rural roads (WT2).

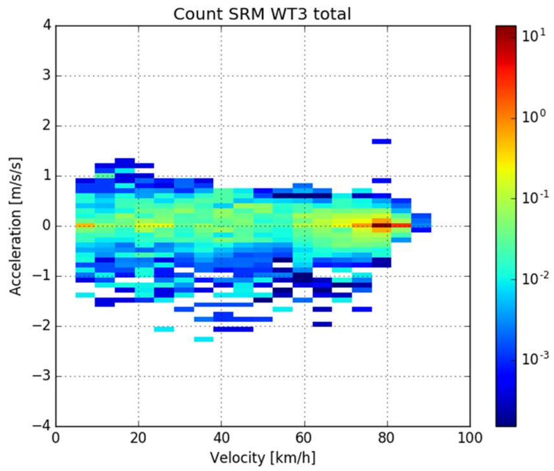

Figure 2-3 Velocity-acceleration distribution of trucks on motorways (WT3).

3 Vehicle monitoring data

Although trucks drive less dynamic than passenger cars or vans, a GPS signal alone has insufficient quality to serve as reliable driving behaviour indicator. Ideally, one should use as much data as possible with (at least) 1Hz CAN velocity information. The emission monitoring data collected by means of TNO's Smart Emission Measurement System, or SEMS, well fits these criteria, and was therefore used for the current update. The UDRIVE data (Bärgman et al., 2017) could also be used for this purpose, but it was unavailable at the time of this analysis.

Almost all monitored vehicles are Euro VI trucks and tractor-semi-trailers. Table 2 shows the main characteristics of the collected data, and a more detailed overview per vehicle can be found in the Appendix. Some vehicles have a distinctive mission profile. Garbage trucks, for example, typically drive at low velocities and have long idling times, with the vehicle stationary. When excluding idling, the average velocity of N3 vehicles, for example, is around 50 km/h, whereas the large contribution of idling causes the average velocity to drop to 27 km/h. The first value of the **q**-vector (q1) incorporates idling, since idling emissions are often substantial.

Table 2 Emission monitoring data used to determine driving behaviour for heavy-duty vehicles, given the available data in September 2017. The average velocities exclude engine-off data.

Vehicle class	Number of vehicles	Driving time [s]	Average velocity [km/h]	Average velocity excluding 0
N2	3	208 792	46	51
N3	12	2 220 377	27	49
M3 (bus)	3	2 056 247	35	39

In this analysis, a distinction is only made between buses and trucks, although many different vehicle types, weights and mission profiles (e.g. garbage collection and regional distribution) occur. Ideally one should also consider payload and road inclination, but these are not yet among the logged parameters, and could not be derived. Furthermore, when more, and more detailed, data will become available, distinctions between mission profiles and power-to-mass ratios can be made in the future.

The data consist of uninstructed driving behaviour, and the vehicles are monitored in their actual daily usage. Due to the limited quality of the GPS signal or missing information in Open Street Maps, about 37% of the emission monitoring data could be coupled to a speed limit, and 13% to a street name. Figure 3-1 shows an example of the possibilities to distinguish between different speed limits at the motorway with this method, though these categories are less important to heavy-duty vehicles, which are equipped with speed delimiters.

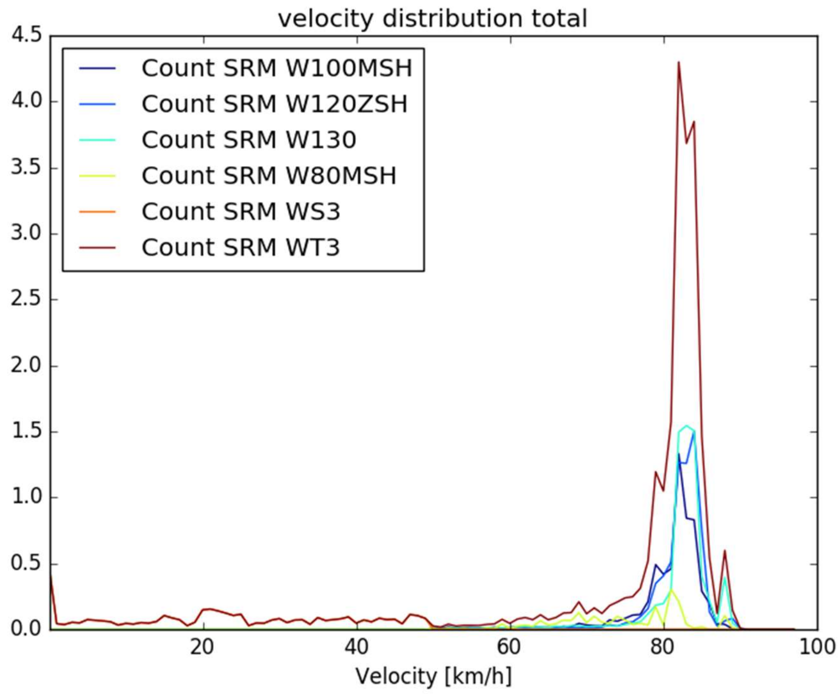

Figure 3-1 Velocity distributions of trucks, categorised into different speed limits and congestion levels at the motorway through speed limit and road type information.

The limited success to match data to Open Street Map information calls for an exploration of alternative options. To determine the road type category independently of Open Street Maps information, the average velocity over 1 kilometre was used. The different results of the two methods are shown in Figure 3-2 (using speed limits, road types and velocity) and Figure 3-3 (using velocity only). The second graph includes more data, but the first covers congestion at motorways, where the average velocity is low but the road type is a motorway. Although the data set of the first method is smaller, it is the method preferred with regard to the goal of this study, and is therefore used to determine the road type category. In future studies, the GPS matching could be improved, so that more data can be collected in order to decrease the uncertainty of the results.

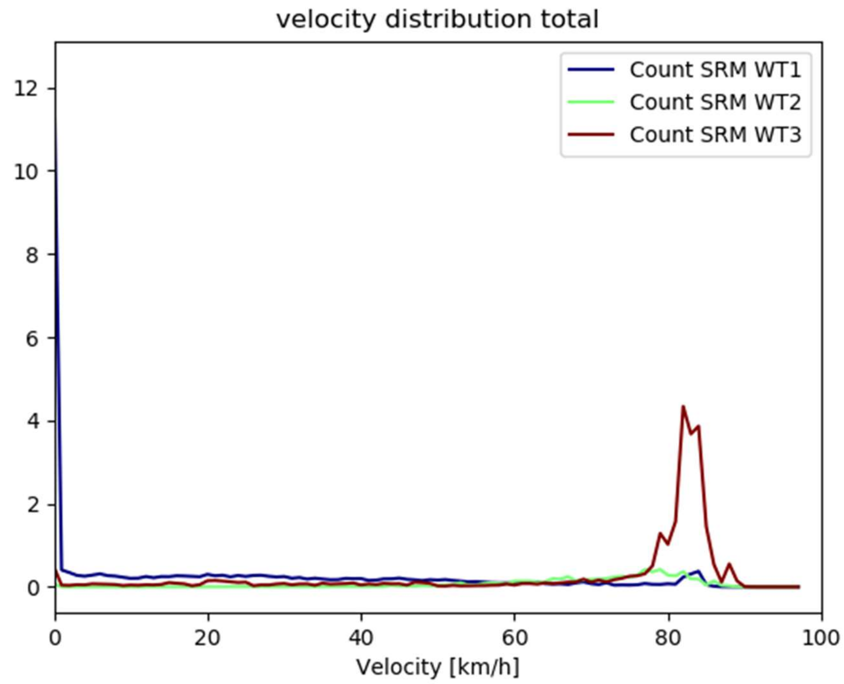

Figure 3-2 Velocity distributions of trucks, categorised into urban, rural and motorway driving through speed limit and road type information.

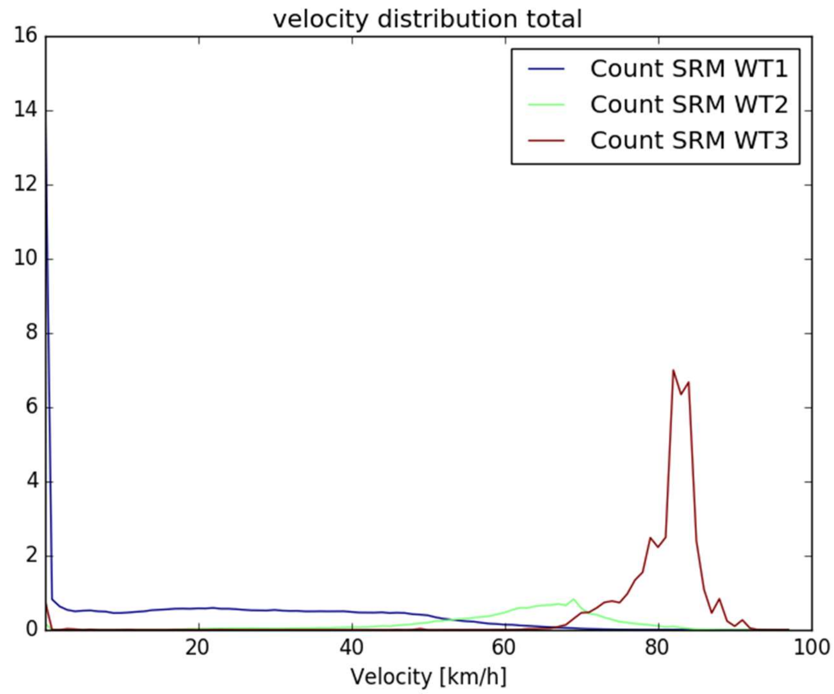

Figure 3-3 Velocity distributions of trucks, categorised into urban, rural and motorway driving through velocity information.

To summarise, the data are divided into the road type categories using the following characteristics:

- instantaneous velocity;
- average velocity over 1 kilometre distance (v_{avg});
- speed limits retrieved from mapping the GPS location to Open Street Maps, taking into account different limits at different times of day;
- road names retrieved from mapping the GPS location to Open Street Maps.

First, the three main road types are distinguished. Urban roads either have an assigned speed limit up until 50 km/h, or a v_{avg} below 50 km/h. From the remaining data, rural roads are selected with speed limits up until 100 km/h and a v_{avg} of over 50 km/h, while the road name does not contain an ‘A’ for (a Dutch) motorway. Finally, motorways are distinguished from the road name retrieved from Open Street Maps, which should in that case contain an ‘A’. Additionally, congestion circumstances are determined from the recorded instantaneous and average velocities at certain road types, as described in Table 1.

4 Resulting driving behaviour parameters

The resulting **q**-vectors for trucks and tractor-semitrailers are shown in Table 3. With respect to the old **q**-vectors (shown in appendix 8.2), there is a higher fraction of idling. The traffic situation WS1 - urban congestion in the city - shows lower velocities, whereas the free-flow circumstances (WF1) result in an additional contribution at high velocities. For all of WT1, WT2 and WT3, the dynamics at medium velocities (q7) are higher than before, which explains an overall increase in emissions when using this new driving behaviour to calculate emission factors.

Table 3 New (2017) driving behaviour q-vectors of heavy-duty trucks and tractor-semitrailers.

q value	WT1	WT2	WT3	WS1	WM1	WF1	WS3
q1	60.76668	0.530299	2.894624	442.9667	91.64415	8.39154	21.53112
q2	55.402	2.415963	5.049817	198.7073	129.376	32.28479	117.8853
q3	27.97051	1.5492	3.209015	68.93069	63.71179	20.56004	65.76944
q4	1.632955	0.14838	0.174914	3.065329	3.20553	1.680343	2.410283
q5	19.01951	36.74786	7.197486	0.244252	4.643171	25.77893	0
q6	17.63025	38.28439	7.804199	0.127324	3.95691	24.22201	0
q7	1.393428	3.930113	1.015154	0.008648	0.350495	2.042078	0
q8	11.38202	11.31787	35.11652	0	0	11.09232	0
q9	8.208337	8.166556	25.45868	0	0	7.98057	0
q10	0.006927	0.005377	0.009362	0	0	0.006958	0

The effect on the emission factors of the changes in heavy-duty driving behaviour differs per road type and congestion category. Average urban emissions rise by at most 30%, while the congestion circumstances on both urban roads and motorways lead to lower estimated emissions. For Euro VI trucks (Table 4) all average emissions rise by 10-20%, while the congestion circumstances show a small decrease of emissions. Euro V emission factors (Table 5) show a similar effect, although the average rural emissions decrease.

Table 4 Example of changes in NO_x emission factors of Euro VI diesel heavy rigid trucks (ZVADEUR6) due to updated driving behaviour.

Road type	**Emission factor** [g/km]		**Difference**
	Old	*New*	
WT1	0.476	0.576	21%
WT2	0.303	0.343	13%
WT3	0.177	0.195	10%
WS1	0.761	0.636	-16%
WM1	0.476	0.555	17%
WF1	0.338	0.468	39%
WS3	0.476	0.476	-1%

Table 5 Example of changes in NO_x emission factors of Euro V diesel heavy rigid trucks (ZVADEUG5SCR) due to updated driving behaviour.

Road type	**Emission factor** [g/km]		**Difference**
	Old	*New*	
WT1	8.97	11.5	29%
WT2	4.81	4.57	-5%
WT3	2.84	2.99	5%
WS1	14.3	14.1	-2%
WM1	8.97	9.98	11%
WF1	6.37	7.38	16%
WS3	8.97	8.70	-3%

5 Discussion and conclusion

The driving behaviour parameters for heavy-duty trucks, tractor-semitrailers and buses were updated in this study. A methodology was developed to divide monitoring data into road type categories, including matching velocity data to road map information.

The effect on the emission factors of the changes in heavy-duty driving behaviour differs per road type category. The average urban emissions rise by at most 30%, while the congestion circumstances on both urban roads and motorways lead to lower estimated emissions.

The driving behaviour should be regularly updated according to this method, such that more and more representative vehicles and mission profiles will be included. In the future, more vehicle monitoring data will become available, allowing for a regular update on driving behaviour in conjunction with the update of emission characteristics. The driving behaviour for trucks can be used to update the emission factors. For buses, it is recommended to first collect more data that consists of urban bus driving.

By improving the labelling of the data with, for example, road inclination and payload, the results could be improved. A separation in driving behaviour could be made between vehicle groups with different power-to-mass ratios. However, in monitoring data payload is not easily available, such that indirect determination of payload must be developed.

The GPS matching between the collected data and Open Street Maps can be improved, such that the matching rate increases with respect to the current 40%. This will exclude any bias due to certain road types being easier to match than others at certain driving behaviours, and it will also decrease the statistical uncertainty of the results because more data can be selected.

6 References

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7 Signature

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8 Appendix

8.1 Data characteristics per vehicle

Table 6 Detailed emission monitoring data parameters used to determine driving behaviour for heavy-duty vehicles, given the available data in September 2017. The average velocity excludes engine-off data.

Vehicle class	Gross Vehicle Weight [kg]	Driving time [s]	Average velocity [km/h]	Vehicle type
N3	19000	183078	64.5	rigid box
N3	27000	316287	19.2	garbage collection
N3	29500	283534	10.8	garbage collection
N3	27500	225036	23.4	garbage collection
N3	14000	78381	29.8	rigid box
N3	19800	47001	40.0	tractor semi-trailer
N3	20000	191969	15.9	garbage collection
N3	8403	128462	44.3	tractor semi-trailer
N3	19000	71812	43.6	rigid box
N3	35000	82756	25.6	garbage collection
N3	21000	86089	39.2	tractor
N3	27500	256949	14.7	garbage collection
N3	19500	165213	31.0	tractor semi-trailer
N2	11990	40806	52.8	rigid truck
N2	11990	155168	44.2	rigid truck
M3	29000	762754	18.9	city bus
M3	14870	916878	48.8	regional bus
M3	14870	275317	33.9	regional bus

8.2 Driving behaviour q-vectors

Table 7 Old (2006) driving behaviour q-vectors of heavy-duty trucks (with trailer “ANH”).

q value	WT1	WT2	WT3	WS1	WM1	WF1	WS3
q1	39.63265	11.123	0.184606	63.41224	39.63265	28.13918	39.63265
q2	90.3676	20.94555	3.987488	144.5882	90.3676	64.161	90.3676
q3	50.49867	10.8359	2.089235	80.79787	50.49867	35.85406	50.49867
q4	1.885444	0.336328	0.034639	3.01671	1.885444	1.338665	1.885444
q5	17.81533	13.66856	6.571971	28.50452	17.81533	12.64888	17.81533
q6	14.18368	12.38813	6.120046	22.69389	14.18368	10.07041	14.18368
q7	0.646785	0.828045	0.471679	1.034857	0.646785	0.459218	0.646785
q8	0	26.009	33.89365	0	0	0	0
q9	0	17.19738	25.51609	0	0	0	0
q10	0	0.006503	0.014851	0	0	0	0

Table 8 Old (2006) driving behaviour q-vectors of heavy-duty trucks (without trailer “SOL”).

q value	WT1	WT2	WT3	WS1	WM1	WF1	WS3
q1	56.4288	9.312353	0.363436	90.28607	56.4288	40.06445	56.4288
q2	117.8875	30.18586	1.962554	188.6199	117.8875	83.70009	117.8875
q3	60.42449	15.56664	1.086806	96.67918	60.42449	42.90139	60.42449
q4	2.096339	0.638058	0.039925	3.354143	2.096339	1.488401	2.096339
q5	5.815781	26.755	5.342508	9.30525	5.815781	4.129205	5.815781
q6	4.670505	25.10934	4.898007	7.472809	4.670505	3.316059	4.670505
q7	0.168116	1.808576	0.44506	0.268986	0.168116	0.119363	0.168116
q8	0	12.08011	36.77972	0	0	0	0
q9	0	7.549578	26.33024	0	0	0	0
q10	0	0.00047	0.032528	0	0	0	0

Table 9 New (2017) driving behaviour q-vectors of regional buses.

q value	WT1	WT2	WT3	WS1	WM1	WF1	WS3
q1	715.1858	0.96237	0	350.6942	197.7467	17.83824	85.38803
q2	123.8389	3.975224	0	184.9097	143.3601	44.4076	130.3347
q3	52.08759	2.475468	0	68.38524	70.43711	28.58998	93.24017
q4	2.252376	0.419874	0	3.821961	7.098049	3.516711	18.24736
q5	0	33.23437	0	0.054348	1.010768	21.84841	0
q6	0	33.2451	0	0.037506	0.870143	19.86274	0
q7	0	3.758493	0	0.000403	0.057937	2.364479	0
q8	0	12.97131	0	0	0	7.416229	0
q9	0	12.55784	0	0	0	9.80192	0
q10	0	3.630518	0	0	0	5.198477	0