J.D.K. Bishop et al., Int. J. Transp. Dev. Integr., Vol. 1, No. 2 (2017) 203–211

REAL-WORLD ENVIRONMENTAL IMPACTS FROM MODERN PASSENGER VEHICLES OPERATING IN URBAN SETTINGS

J.D.K. BISHOP[1], N. MOLDEN[2] & A.M. BOIES[1]
[1]Department of Engineering, University of Cambridge, Cambridge, UK.
[2]Emissions Analytics, Manor Farm, Winchester, UK.

ABSTRACT

Real-world testing of a set of modern vehicles show that most petrols meet their Euro standards for nitrous oxides (NO_x), while most diesel vehicles exceed them. However, that some diesel vehicles met their Euro standards implies exceedances are not peculiar to the fuel. Likewise, the compliance of the tested petrol vehicles with the standard does not mean all petrol vehicles do. Engine maps were synthesized which reproduced trip level emissions to within 10% of that gathered under real-world driving conditions. Average velocity alone, such as what is used in COPERT, is a poor predictor of emissions. Stepwise linear models showed NO_x emissions could be predicted accurately by incorporating other metrics, such as maximum deceleration and the variance of velocity over the driving cycle. The models were validated on three driving cycles where all vehicles met their Euro standards, save Euro 6 diesel vehicles on the US highway cycle. COPERT overestimated NO_x from all vehicles. More work is required to combine driving cycle metrics with vehicle characteristics, such as mass and peak engine torque, to identify the conditions under which vehicles exceed their Euro limits.

Keywords: COPERT, diesel vehicles, engine maps, Euro standards, NO_x emissions, PEMS, vehicle simulation, urban emissions.

1 INTRODUCTION

Reducing nitrous oxides (NO_x) is a challenge which persists across time and space. In 2012, transportation accounted for half of NO_x emissions in the EU-28 (using European Environment Agency data sourced through the European statistical office, available online at http://ec.europa.eu/eurostat/data/database). Then, 9% of Europeans were exposed to annual NO_2 concentrations which exceeded World Health Organisation guidelines (see European Environment Agency CSI004 Indicator, available online at http://www.eea.europa.eu/data- and-maps/indicators/exceedance-of-air-quality-limit-3/assessment.) of 40 μg/m^3. Most of these exceedances occurred at traffic stations near roads. The result of this long-term exposure was 828,000 years of lives lost and 72,000 premature deaths [1]. These emissions have not fallen as fast as the regulations on emissions of NO_x from combustion-related activities suggest. Recent studies show emissions of NO_x from modern vehicles exceed regulated limits by seven times [2].

Inventories of emissions from vehicles are calculated using the Computer Programme to calculate Emissions from Road Transport (COPERT) in Europe and the Motor Vehicle Emission Simulator (MOVES) in the US. Emission factors from COPERT and MOVES are based on average speed and vehicle specific power, respectively. Both methods are based on data collected from vehicles tested on dynamometers over regulated driving cycles. The discrepancy between regulated and real-world energy use and emissions cited above arises

This paper is part of the proceedings of the 22nd International Conference on Urban Transport and the Environment (Urban Transport 2016)
www.witconferences.com

ISSN: 2058-8305 (paper format), ISSN: 2058-8313 (online), http://www.witpress.com/journals
DOI: 10.2495/TDI-V1-N1-203-211

because regulated cycles do not reflect actual driving accurately. COPERT and MOVES emissions factors may be limited further in their ability to predict emissions accurately based on the amount of data available for novel vehicle power trains. For example, the latest COPERT emissions factors use data from 81 Euro 5 vehicles (31 petrol, 50 diesel) and 20 first-generation, Euro 6 vehicles (one petrol, 19 diesel) [3], while MOVES emissions factors are based on data from 2.3 million tests over 500,000 vehicles but only up to calendar year 2005 [4].

Therefore, there is a need to quantify the real-world environmental impacts from modern passenger vehicles operating in the urban environment. This work adopts a top-down approach by using data collected by Emissions Analytics (EA) from 37 vehicles – six Euro 5 petrol, nine Euro 5 diesel, eight Euro 6 petrol and 14 Euro 6 diesel – equipped with portable emissions measurement systems (PEMS) driving under real-world motorway and non-motorway conditions west of London between May and November 2014. Each vehicle was driven on the same route of almost 88 km. Average trip time and speed was 9,100 s and 40 km/h, respectively. Data was collected using a Semtech-DS PEMS equipped with a GPS unit and data was reported on a per-second basis.

There are two analyses provided in this article to quantify the environmental impacts (trip level NO_x emissions) of the test vehicles: first, their measured emissions are compared to both the Euro limit and what they are certified to emit over the New European Driving Cycle (NEDC); and second, the influence of Euro standard, fuel type and drive cycle metrics, such as average speed and acceleration, on emissions is investigated.

2 METHODS

2.1 Trip level emissions

The post-processing of the PEMS reports NO_x emissions, both on absolute basis and normalized to g/km. Additionally, the UK Vehicle Certification Authority (VCA) reports fuel economy, emissions and noise of new vehicles sold in the UK by make, model and description. NO_x emissions limits for Euro 5 and Euro 6 vehicles [5] are given in Table 1. The three emissions – measured, NEDC and Euro limit – were compared.

2.2 Influence of vehicle and driving on emissions

This analysis investigated how Euro standard, fuel type and driving cycle metrics, such as average speed and acceleration, influenced NO_x emissions. There were three steps to this analysis:

1. Extract maps of NO_x emissions from the PEMS testing of the vehicles on the EA driving cycle;
2. Simulate the vehicle with engine and emissions maps on other regulated driving cycles covering urban, rural and motorway driving; and
3. Derive a linear regression model of NO_x emissions as a function of driving cycle characteristics.

Engine maps of NO_x emissions are obtained most often using chassis or vehicle dynamometer testing. This process is time-consuming and expensive and yields steady-state maps as

Table 1: Physical characteristics of vehicles, sales volumes and associated emissions limits.

Attribute	Audi A1	Audi A3	Skoda Octavia	VW Golf
Test mass (kg)	1,035	1,205	1,205	1,474
Effective drag, C_dA (m^2)	0.62	0.55	0.57	0.7
Wheelbase (m)	2.5	2.6	2.7	2.7
Max engine torque (Nm)	160	200	250	340
Top gear number	5	7	6	6
Coefficient of rolling resistance, C_{rr}	0.007	0.011	0.011	0.007
Database code	A10	B14	A16	B18
Sales volume in 2014	24,000	21,000	42,000	75,000.000
Rank (1 = largest volume)	24	34	9	4.000
Fuel	Petrol	Petrol	Diesel	Diesel
Euro standard	5	6	5	6
Euro limit (gNO_x/km) [5]	0.06	0.06	0.18	0.080
NO_x emissions on NEDC (g/km)	0.12	0.035	0.12	0.046

the usual output. However, steady-state maps do not represent transient driving accurately. Likewise, the regulated driving cycles which may be used to generate transient maps in the lab do not represent real-world driving.

Bishop et al. [6] developed a method to generate engine maps of fuel use and emissions from vehicles under real-world driving conditions. This method was applied to four passenger vehicles in the EA test fleet. These vehicles were chosen based on two inputs: the first was that their NO_x emissions were representative of the EA fleet; and their sales volume, reflecting their popularity in the UK and proportion on the road (sales volumes for new vehicles by generic model can be found in UK Department for Transport statistics Table VEH0161 which is available online at https://www.gov.uk/government/ statistical-data-sets/ veh01-vehicles-registered-for-the-first-time). Table 1 lists the exemplar vehicle make, model, fuel, Euro standard and numbers sold in 2014. Models of these vehicles were created in ADVISOR to derive their engine maps.

Each vehicle and engine map of NO_x emissions (g/s) were simulated over nine regulated driving cycles and the original EA test cycle (training cycles). Trip level NO_x emissions were compared against 25 driving cycle metrics. The training cycles and associated metrics are listed in the Appendix.

The influence of predictor variables (driving cycle metrics) on NO_x emissions was investigated using a stepwise linear regression. This Matlab function analyses the impact of each predictor variable, both individually and when combined with other predictor variables in a product. The returned p-values and associated weights indicate the relative importance of each predictor or combination of predictors. In each case, predictors were removed if they did not exert significant influence on the response variable.

Using 25 metrics to predict NO_x emissions could yield models comprising constants, predictors raised to various powers and combined as products. The aim was to find the most simple model in terms of the number of metrics and how they were combined with each other.

This relationship was validated using three cycles – the HWFET, UDDS and JC08 – which were not part of the training set. These validation cycles were selected because their average speed was higher than 10 km/h which is the minimum speed which the COPERT expression is defined over for petrol and diesel vehicles. Emissions (simulated, modelled and estimated using COPERT) over these validation cycles were compared.

3 RESULTS

3.1 Trip level emissions

We expect the emissions from the EA test and over the NEDC to be lower than the Euro limits if they indicated real progress in reducing NO_x emissions. Moreover, we expect measured and NEDC emissions to be similar if the NEDC reflected real-world driving accurately. Figure 1 illustrates the trip level NO_x emissions on the EA test and over the NEDC in blue and yellow bars, respectively [7]. The Euro limit is illustrated with a red line.

As expected, trip level NO_x emissions on the NEDC for each vehicle were less than the Euro limit. However, there was large variation in the distance between emissions on the NEDC and the Euro limit, particularly for Euro 6 vehicles. Many Euro 6 diesels reported emissions on the NEDC well below the Euro limit (range 0.019 g/km for B11 to 0.074 g/km for B4 and B7), with three (B4, B7 and B21) just making the standard with emissions of 0.071–0.074 g/km. All Euro 6 petrol vehicles reported NO_x emissions on the NEDC well below the Euro limit, from 0.018 g/km for B26 to 0.045 g/km for B25, relative to a Euro limit of 0.06 gNO_x/km.

All petrol vehicles, but one (A6 with 0.16 g NO_x/km relative to a Euro 5 limit of 0.06 g NO_x/km), met their respective Euro standards under real-world EA testing. In contrast, most diesel vehicles failed to meet their respective Euro standard on real-world testing. A16 and A20 were the only Euro 5 diesels with NO_x emissions below 0.18 g/km, at 0.15 g/km and 0.10 g/

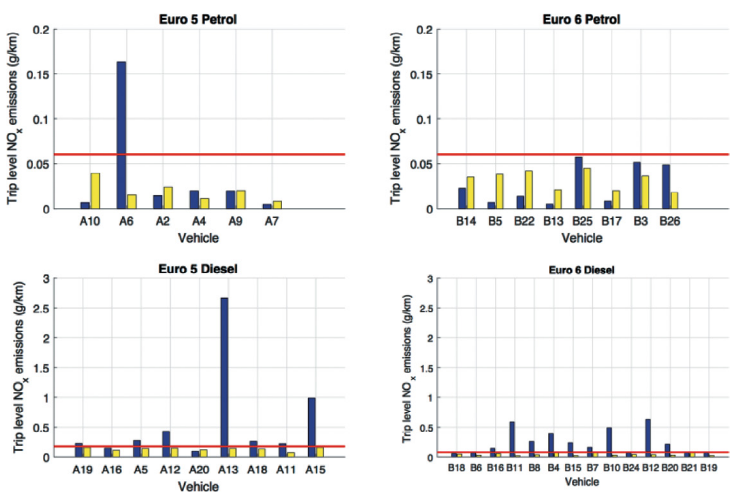

Figure 1: Average NO_x emissions (g/km) for Euro 5 and Euro 6 vehicles using petrol and diesel, where blue bars represent the emissions measured using PEMS; yellow bars represent the emissions expected on the NEDC test; and the red line is the Euro limit.

km, respectively. Likewise, B18, B6 and B24 were the only Euro 6 diesels to meet the 0.08 g/km limit, at 0.056, 0.071 and 0.071 g/km, respectively.

A minority of diesel vehicles tested met their Euro limits. This implies that the exceedance of Euro limits is not a function of the fuel solely, but may be dependent on the vehicle make, model and specification. Similarly, the absence of petrol vehicles exceeding their Euro limits cannot imply all petrol vehicles are compliant.

3.2 Emissions as a function of vehicle and driving characteristics

Four vehicles were selected from the EA database to represent each of the four combinations of Euro standard and fuel type. These vehicles had NO_x emissions which were representative of their respective groups. Necessarily, this analysis excluded vehicles emitting at the high and low end of the range. Instead, this section shows that NO_x emissions can be reproduced accurately using a combination of driving cycle metrics.

The engine maps for the four vehicles are shown in Figure 2. Simulating the EA test cycle for each vehicle using these maps returned trip level NO_x emissions within 10% of that measured. The maps of NO_x emissions are plotted on the same scale to allow easy comparison in peak emissions across Euro standards and fuel types. Highest and lowest NO_x emissions are 0.065 g/s and 10^{-5} g/s and occur for the Euro 6 diesel and Euro 6 petrol vehicles, respectively.

Recall the COPERT equation has a quadratic form, with NO_x emissions as a function of fuel type, Euro standard and average speed. Using a linear regression model to fit NO_x emissions to average speed yielded a poor fit with $R^2 < 0.58$ across the four vehicles. Therefore, average speed alone may be insufficient to predict fuel economy and NO_x emissions accurately. Figure 3 illustrates how COPERT (orange broken line) overestimates emissions for the vehicles tested (Table 2).

The stepwise linear regression on all combinations of driving cycle metrics across the training cycles showed that trip level NO_x emissions could be predicted accurately ($R^2 > 0.86$)

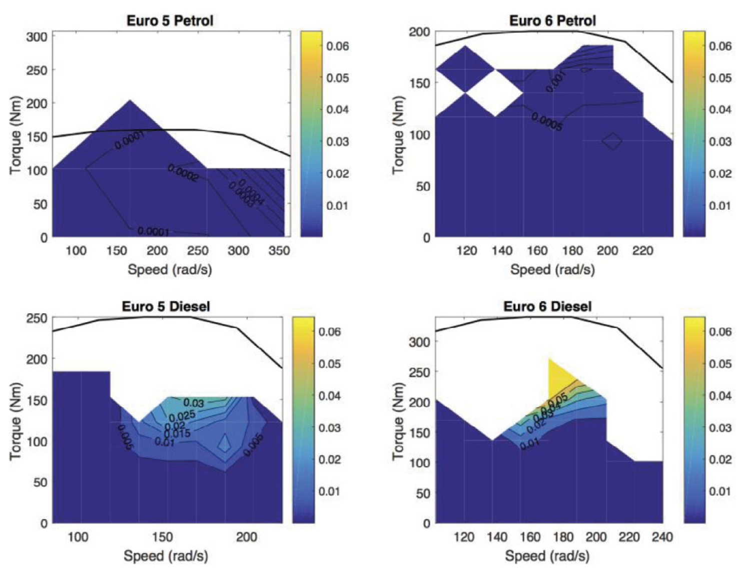

Figure 2: Engine maps of NO_x emissions (g/s) for Euro 5 and 6 vehicles using petrol and diesel. Maps are plotted on the same scale.

Table 2: Comparison of fuel use and emissions obtained on smoothed EA test across four high-selling vehicles and when simulated using extracted engine maps.

	Audi A1	Audi A3	Skoda Octavia	VW Golf
EA test outputs				
Total emissions (g)	º0.84	1.8	13	4.9
Normalized emissions (g/km)	0.0063	0.02	0.15	0.055
Simulated outputs using engine maps				
Total emissions (g)	0.82	1.8	13	4.4
Normalized emissions (g/km)	0.0062	0.02	0.15	0.050
Error between EA test and simulated (%)				
Total emissions (g)	2.8	0.15	–2.9	9.1
Normalized emissions (g/km)	1.6	0	–3	9.2

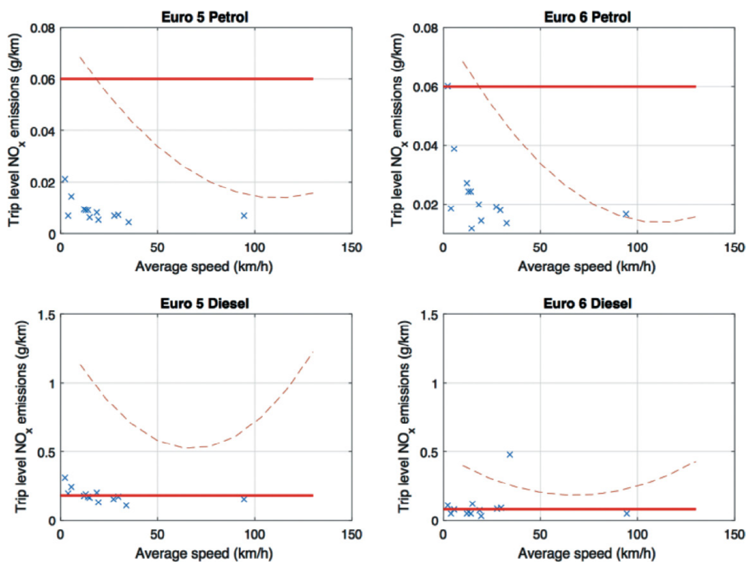

Figure 3: Simulated trip level NO_x emissions across all driving cycles (blue crosses) with corresponding COPERT function (orange broken line), by vehicle Euro standard and fuel type. Euro emissions limits are shown as a red line.

using velocity and acceleration with additional terms characterizing the distribution of these metrics over the driving cycle. The models for each vehicle are given by

$$0.036 - 0.00068 \cdot v_{max} + 3.9e - 6 \cdot v_{max}^2 \text{ for Euro 5 petrol, } R^2 = 0.86 \quad (1)$$

$$0.14 - 0.0039 \cdot v_{max} + 3e^{-6} . v_{max}^2 \text{ for Euro 6 petrol, } R^2 = 0.92 \quad (2)$$

$$0.14 - 0.0039 \cdot v_{max} 2.1e^{-4}.\ v_{var} - 0.28 \cdot acc_{var} - 0.0049 \cdot v_{iqr} + 1.3e^{-4}.\ v_{max}^2 + 0.36.\ acc_{var}^2 \quad (3)$$

for Euro 5 diesel $R^2 = 1$

$$-\ 0.032 - 0.026 \cdot dec_{max} - 7.8e^{-5}.\ v_{var} + 0.017 \cdot acc_{var} + 1.1e^{-6}.\ v_{var}^2 - 0.27 \cdot acc_{var}^2 \quad (4)$$

for Euro 6 diesel, $R^2 = 0.99$,
where full names of the driving cycle metrics are given in Appendix 5.

Trip level NO_x emissions simulated over the validation cycles using engine maps were compared to emissions calculated using the models above and the COPERT expression. The bars in Figure 4 are grouped in the three validation cycles, where emissions from the full vehicle power train simulation using the engine maps are shown in blue. All petrol and diesel vehicles display trip level NO_x emissions below their respective Euro limits (red lines). Notably, Euro 6 petrols have higher emissions than Euro 5 petrols over the three cycles. The model predictions were least accurate for the Euro 6 diesel vehicle.

Figure 1 shows that vehicles in each fuel type exist which meet their required Euro standard. This work could be conducted using a high-emitting vehicle which would give different

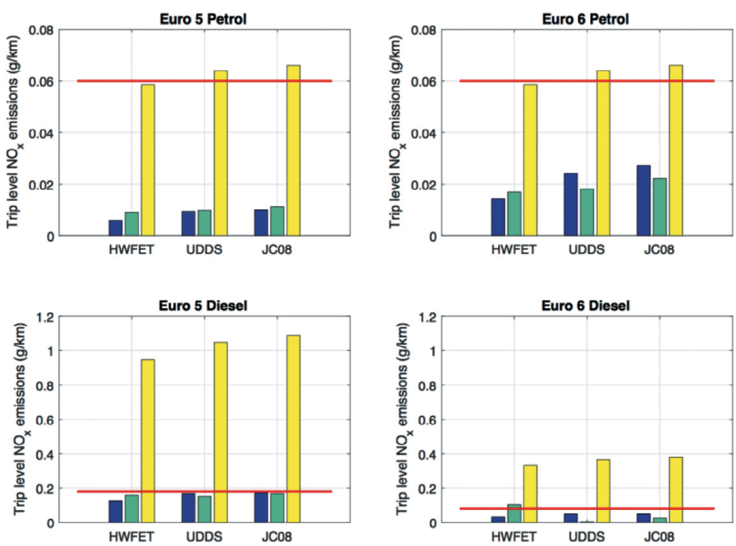

Figure 4: Comparison of NO_x emissions derived from vehicle simulations using engine maps (blue), from the regression model using driving cycle metrics (green) and using the COPERT form (yellow). The red line illustrates the respective Euro emissions limit.

results, relative to both the Euro limit and COPERT estimate. Therefore, further work should extend this method to all vehicles in the EA database for each Euro standard/fuel type combination. This extended analysis would allow vehicle characteristics, such as mass and peak engine torque, to be included in the model with driving cycle characteristics. Consequently, there would be a stronger evidence base for determining the conditions under which vehicles exceed their Euro limits and by how much.

4 CONCLUSIONS

NO_x emissions from transportation contribute to poor urban air quality and prolonged exposure has adverse effects on human health. Testing of modern diesel vehicles operating under real-world conditions suggests NO_x emissions exceed the regulated Euro limits significantly. Consequently, both the Euro limit values and the national inventories derived from COPERT functions underestimate the true quantity of NO_x emitted and overall human exposure. This article presents a novel way to extract engine maps of NO_x emissions from on-the-go driving to simulate vehicle performance over driving cycles. Models were derived which combined velocity, acceleration and measures of the dispersion of these values across the driving cycle to predict NO_x emissions accurately. The validated models indicated that the chosen petrol and diesel vehicles met their Euro limits in most cases. Further work includes testing more vehicles of varied size (mass) and peak engine torque to build a more robust predictor of NO_x emissions incorporating both characteristics of the vehicle and driving. This is important to determine under what conditions the NO_x limits are exceeded.

ACKNOWLEDGEMENTS

The authors acknowledge the UK EPSRC funding provided for this work under the Centre for Sustainable Road Freight Transport (EP/K00915X) and the Energy Efficient Cities Initiative (EP/F034350/1).

REFERENCES

[1] EEA, *Air quality in Europe – 2015 report*. European Environment Agency, 2015.
[2] Franco, V., Sànchez, F.P., German, J. & Mock, P., Real-world exhaust emissions from modern diesel cars: A meta-analysis of PEMS emissions data from EU (Euro 6) and US (Tier 2 Bin 5/ULEV II) diesel passenger cars – Part 1: Aggregated results. White paper, The International Council on Clean Transportation, Berlin, 2014.
[3] Rexeis, M. et al., *Update of Emission Factors for EURO 5 and EURO 6 vehicles for the HBEFA Version 3.2*, Graz University of Technology: Graz, chapter Exhaust emissions from road transport, 2013.
[4] USEPA, Development of emission rates for light-duty vehicles in the motor vehicles emissions simulator (moves 2010). Technical Report EPA-420-R-11- 011, Environmental Protection Agency, Washington DC, 2011.
[5] EC, *Type approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and Euro 6) and on access to vehicle repair and maintenance information*. European Parliament and the Council, 2007.
[6] Bishop, J.D.K., Stettler, M.S., Molden, N. & Boies, A.M., Engine maps of fuel use and emissions from transient driving cycles. *Applied Energy*, 2016.
[7] Mackovjak, J.M., *Light Duty Vehicle NO_x Emission Factor Modelling Utilizing Speed and Vehicle Specific Power Measured from a Portable Emission Measuring System*. Master's thesis, University of Cambridge, 2015.

5 APPENDIX

The vehicles were tested over the training driving cycles of the following:

1. New European Driving Cycle (NEDC)
2. (France) Cycle developed by INRETS using driving around Lyon, France (INRETS)
3. (US) California Unified Cycle (LA92)
4. (US) Inspection and Maintenance driving cycle (IM240)
5. (US) New York City Cycle (NYCC)
6. World Harmonized Light Vehicles Test Procedure (WLTP)
7. Mixed urban, suburban and motorway cycles developed over the European FP5 project ARTEMIS (ARTEMIS)
8. Artemis Urban cycles developed over the European FP5 project ARTEMIS (ARTEMIS Urban)
9. EA cycle
10. (US) Supplemental test procedure which includes aggressive highway driving (US06)

and validated over:

1. (US) Highway Fuel Economy Test (HWFET)
2. (US) Urban Dynanometer Driving Schedule (UDDS)
3. (Japan) JC08

Fuel economy and NO_x emissions were evaluated over the driving cycle metrics of the following:

- Running (v_{run}), average (v_{avg}) and maximum velocity (v_{max})
- Number of accelerations and decelerations per km
- Average (sp_{avg}) and variance of specific power (sp_{var})
- Average (acc_{avg}) and root mean squared of acceleration (acc_{rms})
- Average deceleration (dec_{avg})
- Number of stops per km
- Trip time
- Proportion of time spent idling, accelerating, cruising and decelerating
- Relative positive acceleration (acc_{rp})
- Kinematic intensity
- Aerodynamic velocity
- Characteristic acceleration
- Maximum acceleration (acc_{max}) and deceleration (dec_{max})
- Variance of velocity (v_{var}) and acceleration (acc_{var})
- Interquartile range of velocity (v_{iqr}) and acceleration (a_{iqr})