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TNO report

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More information, Less emissions
Estimating the real-world CO_2 emissions of passenger cars based on vehicle properties

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Summary

Vehicle manufacturers are obliged to supply official fuel consumption data. However, legislation dictates that this fuel consumption must be measured over a standard test cycle, which has limited relation to real world driving and vehicle use. As a result, the official fuel consumption numbers severely underestimate real-world fuel consumption, and consequently real-world CO_2 emissions ($RWCO_2$). However, other aspects, such as idealized testing and administrative corrections, also play a role in this difference.

In the interest of informing the consumer, the project 'More Information Less Emissions – Empowering Consumers for a Greener 21st Century' (MILE21,[1] see also www.mile21.eu) aims to develop a platform via which drivers can investigate the fuel consumption and emissions of vehicles on the European market.
Fuel consumption and CO_2 emissions are directly related through the carbon content of the fuel. The initial model for $RWCO_2$ emissions, Model M1, is dependent on vehicle properties. This initial model will be expanded at a later date, based on monitoring (Model M2) and consumer (Model M3) data.

Here we present Model M1 for the prediction of $RWCO_2$ emissions. This model is based on real-world fuel consumption of passenger cars provided by the Dutch fuel card provider Travelcard Nederland BV. A subset of the Travelcard data is used which includes petrol (including petrol hybrid and petrol plug-in hybrid) and diesel passenger cars with a mass (in running order) less than 2200 kg and a build year of 2009 or later. This subset contains around 220,000 vehicles and has been reported on before.

Model M1 is based on a mass-factor term which outlines the vehicle-mass dependence of the real-world fuel consumption, as well as build year dependent offset. This build year dependency reflects changes in vehicle technology over time. On average, for the entire vehicle subset, the CO_2 contribution due to mass is around 100 g/km of the total CO_2, while the build year dependent offset is around 50 g/km. The addition of terms to the model based on the power, engine size, and frontal area of the vehicles was also investigated, but did not lead to a statistically significant improvement. Model M1 has a standard deviation in CO_2 emissions of around 26 g/km, which may largely be attributed to driver behaviour. The representativeness of Dutch driver behaviour for Europe will be investigated further in a second model which incorporates differences in usage and conditions from monitoring data, expected in 2020.

[1] MILE21 is a project co-financed by the LIFE+ program of the European Union, agreement number LIFE17 GIC/GR/000128.

Contents

1 Introduction

1.1 Context

When purchasing a new passenger vehicle, there are several reasons why a consumer may be inclined to choose a fuel-efficient model. These reasons could include running costs, tax benefits, environmental impact, or resale value. Although vehicle manufacturers are obliged to supply official fuel consumption data, legislation dictates that the consumption must be measured over a standardised test cycle. This test cycle often has little relation to real world vehicle usage. As a result, the official fuel consumption numbers severely underestimate real-world fuel consumption, and consequently real-world CO_2 emissions ($RWCO_2$). Additional information about vehicle fuel consumption and emission may be helpful when making vehicle purchasing decisions. In order to provide additional information, analysis of real-world fuel consumption is necessary to give a better estimation of $RWCO_2$. Using this analysis, predictions for CO_2 emissions can also be made for new passenger vehicles, based on vehicle properties. Here we present a model, Model M1, for predicting $RWCO_2$ based solely on vehicle properties. Model M1 will be expanded at a later date, based on monitoring (Model M2) and consumer (Model M3) data.

This model is developed within the project 'More Information Less Emissions – Empowering Consumers for a Greener 21st Century' (MILE21,[2] see also www.mile21.eu). MILE21 aims to develop a platform via which drivers can investigate the fuel consumption and emissions of vehicles on the European market. The values for fuel consumption and emission on the platform will be provided via quantitative models, type-approval vehicle property data, and (later in the project) large-scale real-world emission data. This large-scale data will be obtained via on-board measurement data, as well as by encouraging consumers to monitor and share their own vehicle's fuel consumption via an online environment.

1.2 Real-world fuel consumption data

TNO routinely analyses the real-world fuel consumption of Dutch passenger cars based on fuelling data provided by Travelcard Nederland BV (see also www.werkelijkverbruik.nl).

[2] MILE21 is a project co-financed by the LIFE+ program of the European Union, agreement number LIFE17 GIC/GR/000128

These analyses have been done for some time (Gijlswijk *et al.*, 2018; Ligterink *et al.*, 2010, 2013, 2014, 2015, 2016), and show that real-world fuel consumption is consistently higher than type-approval figures provided by manufacturers. The creation of the Model M1 is based on data collected in the Travelcard database, which contains data for around 900,000 vehicles. For a discussion of the validity of extrapolating conclusions from this database to the Dutch fleet, see also (Gijlswijk *et al.*, 2018).

Travelcard is a fuel card provider based in the Netherlands. The Travelcard fuel cards are used to purchase fuel at Dutch fuel stations, as well as at more than 43,000 fuel stations across Europe. Per fuel purchase, the amount of fuel purchased and the odometer setting is recorded. The average fuel consumption for each vehicle is then calculated by dividing the sum of the fuel purchased by the sum of the kilometres driven, as per (Gijlswijk *et al.*, 2018). By matching Travelcard data to registration data from the Dutch road vehicle authority RDW, other relevant technical properties are recorded for each vehicle. The frontal area of a number of vehicles is included by Travelcard Nederland BV.

The current scope for Model M1 is petrol, diesel, hybrid, and plug-in passenger cars with a mass (in running order) less than 2200 kg and a build year of 2009 or later. In the Travelcard data there are around 92,000 petrol vehicles, 113,000 diesel vehicles, 9,000 hybrid vehicles (excluding plug-ins), and 2,000 plug-in hybrid vehicles. The representativeness of this subset and Dutch driving for Europe will be investigated in the development of the second Model M2, which is expected in 2020.

2 Model outline

The Model M1 is based on the mass and build year dependence of $RWCO_2$. The two variables mass and build year can be combined to predict CO_2. For each vehicle the vehicle mass M may be multiplied by a mass factor a (see Table 1), while a contribution dependent on build year $b(t)$ is added as a discrete value (for values see Table 2). An example for this calculation is given later in this section.[3]

$$CO_2 = a\,M + b(t).$$

Table 1: Mass factor *a* for petrol, diesel, petrol hybrid, and petrol plug-in hybrid passenger cars.

	Petrol	Diesel	Hybrid	Plug-in
Mass factor a	0.0810	0.0727	0.0298	0.0912

The mass factor shows the difference in engine efficiency between a petrol and diesel car. Per gram CO_2 both petrol and diesel fuel deliver about the same amount of energy: 73 g/MJ. For the same vehicle mass the CO_2 emissions for petrol vehicles is 11% higher than diesel, which is related to the engine efficiency.

Table 2: Build year $b(t)$ contribution for petrol, diesel, petrol hybrid, and petrol plug-in hybrid passenger cars

Build year $b(t)$	Petrol	Diesel	Hybrid	Plug-in
2009	68.9	49.7	97.2	
2010	63.7	46.4	90.3	
2011	60.7	44.9	89.9	
2012	54.8	41.1	87.7	-31.1
2013	52.5	38.5	89.2	-28.8
2014	52.4	38.5	88.0	-25.6
2015	52.9	37.7	84.8	-24.1
2016	51.6	39.5	83.6	-18.8
2017	54.6	41.5	90.1	-25.9
2018	55.7	42.9	91.4	-34.7

The offset shows substantial improvements of the engine efficiency of especially petrol cars, independent of the mass, i.e., related to the generic efficiency at low load. The offset decreases by 13 g/km for petrol, and 7 g/km for diesel. For hybrids and plug-in hybrids the relation between mass and CO_2, and therefore the offset, is rather complex (mass also plays a role in energy recovery). In these cases little conclusions can be drawn, but the stability of the results over the years does suggest the presence of underlying principles.

[3] A worksheet for this calculation is given in the Appendix.

2.1 Example calculation using Model M1

Here we calculate an approximation of the CO_2 emissions for a diesel vehicle, built in 2017, with an empty weight of 1354 kg.

Essential Vehicle Parameters

Vehicle mass in running order (in kg) Mass in running order is the mass of the empty vehicle plus 100 kg.	*1454*	(1)
Vehicle type (petrol, diesel, hybrid, plug-in)	*Diesel*	(2)
Build year	*2017*	(3)

Model factors

Mass factor a Look up value for vehicle type from Table 1	*0.0727*	(5)
Build year factor $b(t)$ Look up value for year and vehicle type from Table 2	*41.5*	(6)

Calculation

Mass term Multiply Box (1) by Box (5): $a \times M$	*105.7*	(7)
Approximation CO_2 (g/km) Add Box (6) and Box (7): $a\,M + b(t)$	*147*	(8)
Approximation fuel consumption (L/100 km) Divide Box (8) by 23.7 for petrol, or 26.5 for diesel fuel equivalent	*5.6*	(9)

3 Model justification

In the section above, an outline of Model M1 was given. Here, the justification for this model is presented. For the development of the model, the link between $RWCO_2$ emission and vehicle properties that are readily available was examined. For this analysis, $RWCO_2$ emissions were obtained by transforming the fuel consumption data recorded in the Travelcard database: one litre of petrol produces 2370 grams of CO_2, while one litre of diesel produces 2650 grams (Gijlswijk *et al.*, 2018).[4] Vehicle properties recorded in the RDW databases include mass (in running order), year of first registration (analogous to build year), power, and engine size. Furthermore, the frontal area was supplied by Travelcard for about 60% of vehicles in their database.

3.1 Mass and build year dependence

As mentioned earlier, Model M1 is based on the mass and build year dependence of $RWCO_2$. The mass of the car is a significant contributor due to the physical forces acting on the car, while build year is important due to the correlation between changes in popular vehicle technology and build year. In Figure 1 and Figure 2 the dependence of CO_2 emissions on mass and build year is shown for the vehicles in the subset. For mass (Figure 1), a clear increasing linear trend is seen between 1000 and 1900 kg for petrol and diesel. Hybrid vehicles show a less obvious increasing trend. As hybrids recover part of the braking energy, a smaller mass dependence is expected. The spread in the result is likely to be caused by the different use patterns of these vehicles and differences in (effectiveness of) hybrid technologies.

A part of the fuel consumption is not mass related. This is covered by adding a discrete factor to the formula. By calculating the discrete value for each build year separately, it reflects the technological changes in efficiency of the engine and gearbox over time. There are different relationships possible between CO_2 emissions and physical properties of the vehicles. But the derived relationship is the simplest and most accurate one, given the unexplained variation due to variations in vehicles usage.

The combination of this behaviour leads to the $RWCO_2$ prediction

$$CO_2 = a\,M + b(t).$$

[4] This relation was established from type-approval data which contained both the fuel efficiency and the CO_2 emissions of the same test.

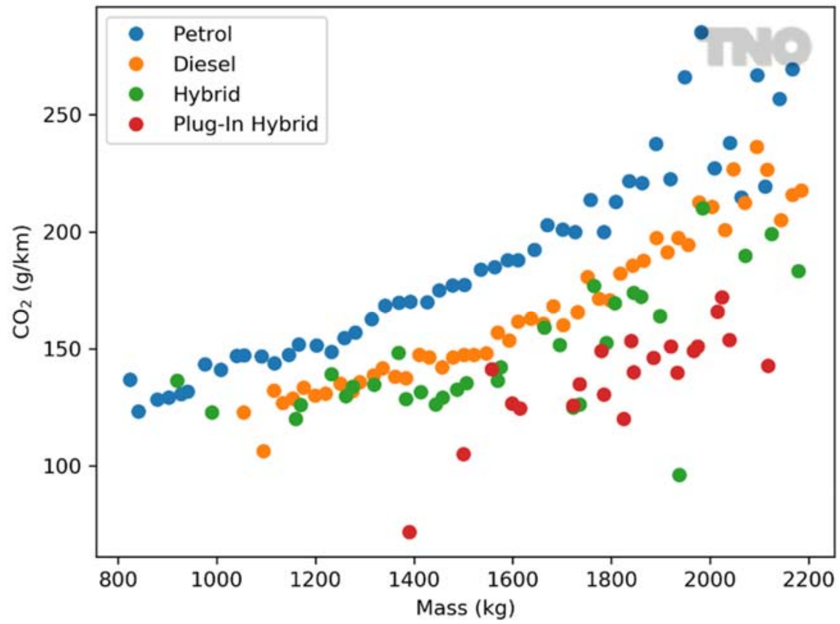

Figure 1: The CO_2 dependence of petrol (blue), diesel (orange), hybrid (green) and plug-in hybrid (red) vehicles in the vehicle subset used for Model M1, on the mass (binned by weight).

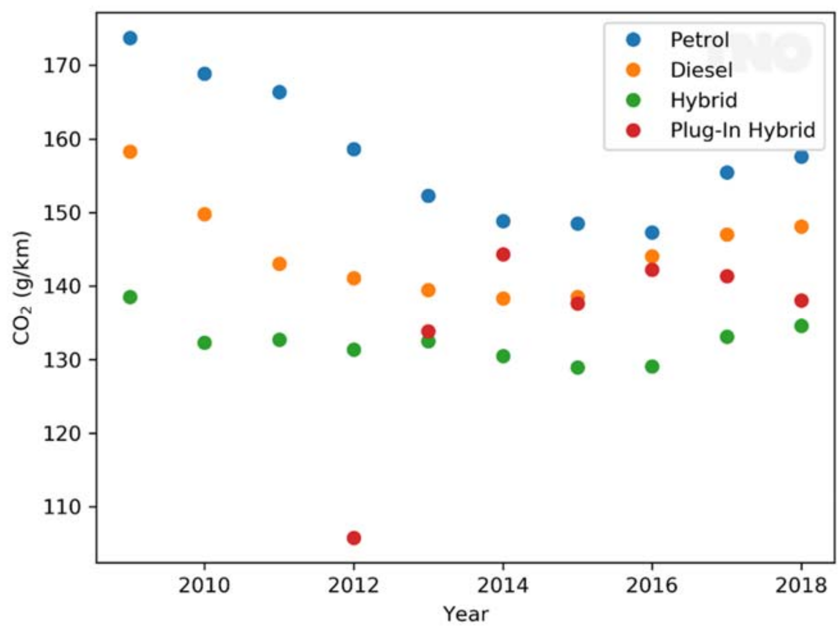

Figure 2: The CO_2 dependence of petrol (blue), diesel (orange), hybrid (green) and plug-in hybrid (red) vehicles in the vehicle subset used for Model M1, on the build year of the vehicle (binned by year). In 2012 the number of plug-in hybrids was very limited.

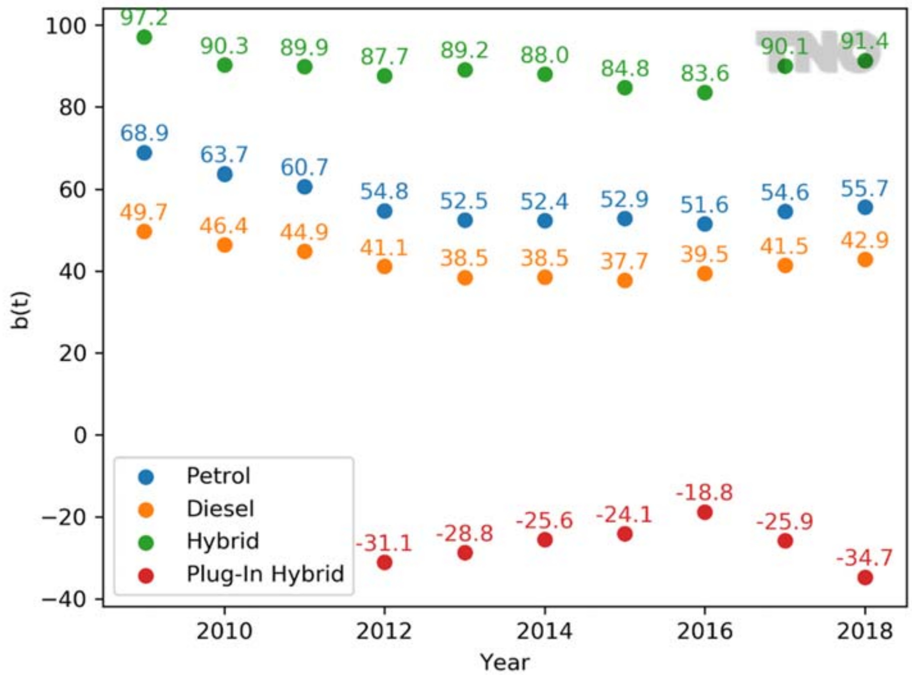

Figure 3: Build Year factor $b(t)$ for petrol, diesel, and hybrid petrol passenger cars as determined using real world CO_2 values obtained in the Netherlands.

Between 2009 and 2015, the build year factors decrease (see Figure 3), implying an increase in drivetrain efficiency. However, from 2015 onwards the build year factors increase again. This phenomenon may be related to financial policies in the years prior to 2015, which favoured vehicles with low type-approval CO_2 values. This resulted in an incentive for manufacturers to minimise type-approval CO_2 values. In 2017, the new WLTP[5] vehicle testing procedure was introduced; the move from the old NEDC[6] standardised test cycle to the WLTP cycle may have led to different priorities for manufacturers. The plug-in build year factors are negative (the plug-in mass factor is also higher), reflecting that electricity acts as an additional source of energy which has not been taken into account in the fuel consumption formula. The plug-in result is therefore very dependent on the charging behaviour of the owner.

On average, for the entire vehicle subset, the CO_2 contribution due to mass is around 100 g/km, while the build year dependent offset is around 50 g/km. For petrol, the average remainder (i.e. $CO_2 - a\,M - b(t)$) is 0.0 g/km with a standard deviation of 26.7 g/km, while for diesel the difference between the model and measured data is (0.0 ± 23.1) g/km, for hybrids (0.0 ± 22.5), and for plug-in hybrids (0.0 ± 31.0). The standard deviation in these models may largely be attributed to driver behaviour and vehicle usage. Driver behaviour may also be influenced by properties of the vehicle, and these are examined as secondary effects below.

[5] Worldwide Harmonised Light Vehicles Test Procedure
[6] New European Driving Cycle

3.2 Secondary effects

The correlation between CO_2 and the vehicle properties mass, build year, power, engine size and frontal area is shown in Table 3. As demonstrated in Figure 1, there is a positive linear relationship between CO_2 and mass. There is a weak linear relationship between vehicle properties and build year, shown also in Figure 2. The correlation coefficients between mass, power, engine size, and frontal area show a strong positive linear relationship between mass and the other three properties. Because of this strong correlation, adding secondary contributions dependent on these properties may lead to over-fitting.

The residual $CO_2 - a\,M - b(t)$ was investigated further for dependencies on the vehicle properties mentioned above. Although this investigation sheds light onto sources of possible discrepancies between predicted CO_2 values and measured $RWCO_2$, including these do not significantly improve the initial Model M1. For completeness, we include a discussion of the residual dependencies below.

Table 3: The pairwise correlation coefficients for CO_2 and the vehicle properties mass, build year, power, engine size and frontal area. ± 1 indicates a perfect positive or negative linear relationship, while 0 indicates no linear relationship.

	Mass	Year	Power	Engine Size	Frontal Area
CO_2	0.42	-0.14	0.32	0.39	0.59
Year	-0.30		-0.29	-0.25	-0.14
Power	0.93			0.83	0.67
Engine Size	0.90				0.71
Frontal Area	0.84				

3.2.1 Mass and build year

The large majority of passenger cars have a mass between 900 and 1800 kg (Figure 4). The secondary effect of the mass on $CO_2 - a\,M - b(t)$ in this region fluctuates around 0. At higher masses, M1 underestimates CO_2 emissions for petrol and diesel vehicles. As shown in Figure 5, M1 is very effective in accounting for the average contribution due to build year, with a maximum average deviation of 2 g/km. In Figure 5, there is a clear spike in hybrid and diesel vehicle numbers built in 2015. This may be attributed to changes in legislation regarding the fiscal treatment of fuel-efficient vehicles, which went into effect on the first of January 2016.

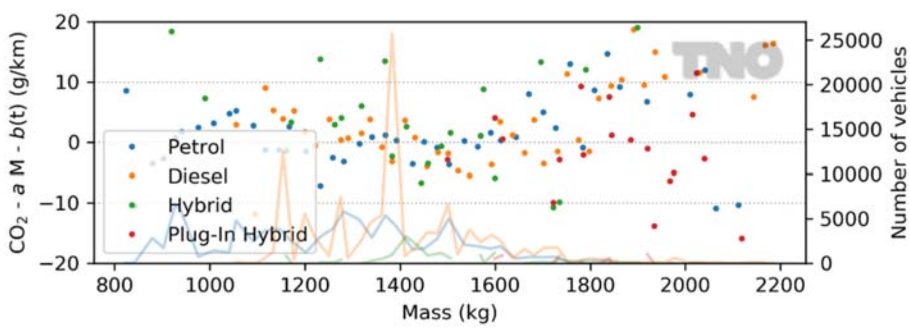

Figure 4: Residual CO_2 dependence ($CO_2 - a\,M - b(t)$) on **mass**, of petrol (blue dots), diesel (orange dots), hybrid (green dots), and plug-in hybrid (red dots) vehicles. The number of vehicles is also indicated (lines). Low vehicle numbers, i.e., below 500 are a source of large variations due to limited statistics.

Other possible causes of the deviation at higher masses are energy consumption by additional equipment in luxury cars, additional losses from four-wheel drivetrains and an unfavourable power to weight ratio (see next paragraph).

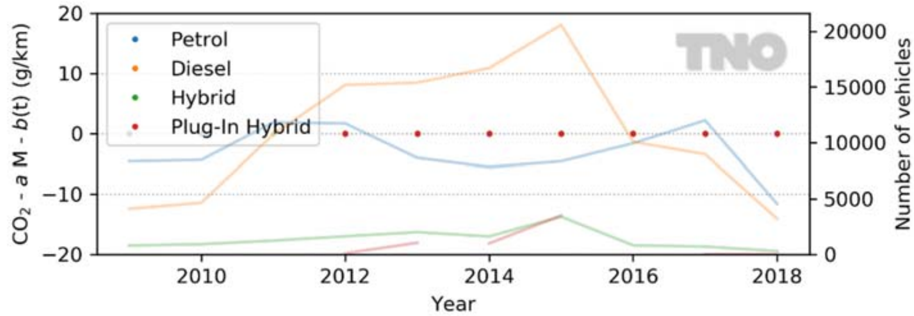

Figure 5: Residual CO_2 dependence ($CO_2 - a\,M - b(t)$) on **build year**, of petrol, diesel, hybrid, and plug-in hybrid vehicles. This variation is minimal: the dots for each fuel type overlap. The number of vehicles per build year is shown by coloured lines.

We note that as the mass contribution should be sufficiently described by the $a\,M$ term, the power, engine size, and frontal area property values are divided by the mass of the vehicle in the analysis below.[7]

3.2.2 *Power*

Considering the power/mass dependency (Figure 6), it can be seen that an estimation using only the mass and year dependencies underestimates CO_2 emissions for vehicles with power/mass ratios less than 50, and larger than 90 kW/tonne. For vehicles in this category, M1 will not be a highly accurate predictor. A large proportion of the diesel vehicles with power/mass ratios less than 50 are vans; these vehicles may also have a larger mass during real-world driving due to larger loads (be they goods or passengers). However, in the region where most petrol and diesel vehicles are found, $CO_2 - a\,M - b(t)$ is around 0. Fewer hybrid vehicles were measured, and their power/mass ratio is less consistently spread between 50 – 90 kW/tonne, which makes it difficult to reach similar conclusions.

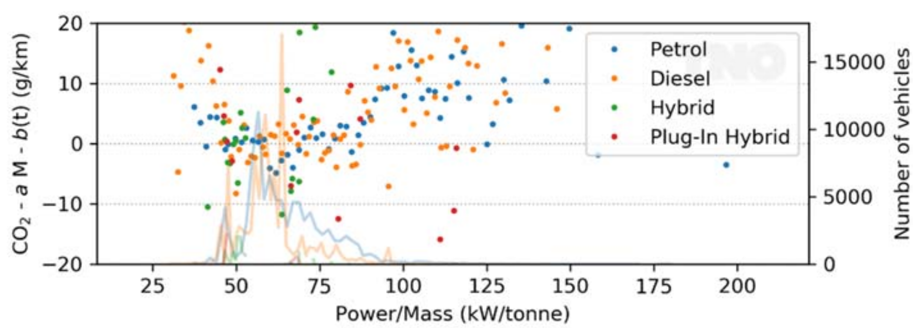

Figure 6: Residual CO_2 dependence ($CO_2 - a\,M - b(t)$) on **power divided by mass**, of petrol (blue), diesel (orange dots), hybrid (green dots), and plug-in hybrid (red dots) vehicles (binned by power/mass). The number of vehicles in these bins is shown by lines in corresponding colours.

[7] These secondary contributions can also be investigated using the worksheet in the Appendix.

3.2.3 *Engine size and frontal area*

For both engine size and frontal area, in the case of petrol and diesel vehicles, $RWCO_2$ shows an approximate linearly increasing relationship (where engine size and frontal area have been divided by mass) in the regions with the most vehicles (see Figure 7 and Figure 8). For hybrids and plug-in hybrids, there is no obvious trend. At low frontal area/mass values, as well as for high engine size/mass values, there is an underestimation of CO_2 emission by Model M1 of up to 20 g/km.
For petrol and diesel vehicles, the linear relationships can be modelled by

$$CO_2 - a\,M - b(t) = c_1\,\mathrm{X} + c_2,$$

where X is the property engine size/mass or frontal area/mass, and c_1, c_2 constants as given in Table 4.

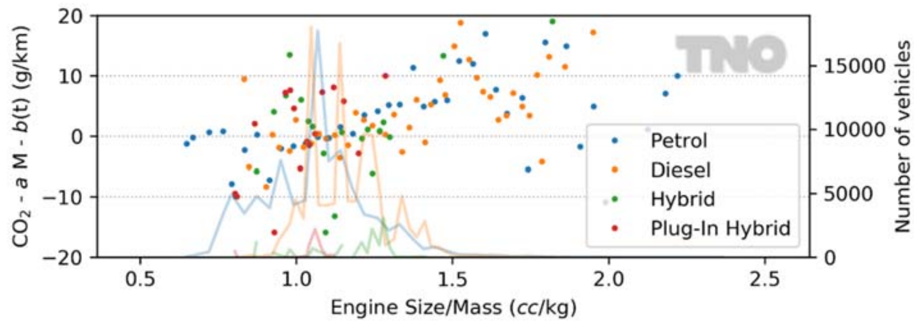

Figure 7: Residual CO_2 dependence ($CO_2 - a\,M - b(t)$) on **engine size divided by mass**, of petrol (blue), diesel (orange dots), hybrid (green dots), and plug-in hybrid (red dots) vehicles (binned by engine size/mass). The number of vehicles is shown by lines in the corresponding colours.

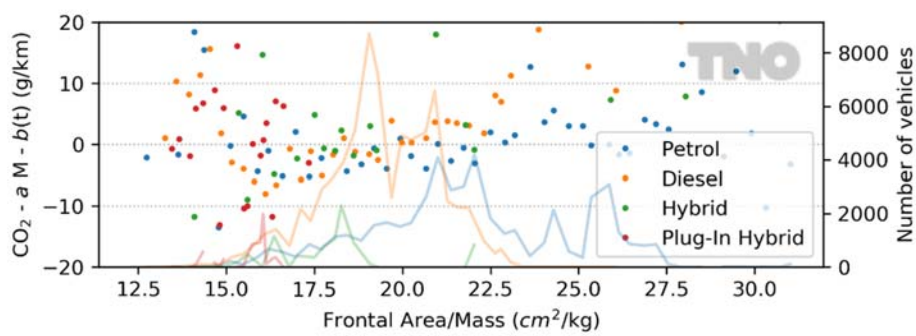

Figure 8: Residual CO_2 dependence ($CO_2 - a\,M - b(t)$) of petrol (blue), diesel (orange dots), hybrid (green dots), and plug-in hybrid (red dots) vehicles on the **frontal area divided by mass** (binned by frontal area/mass, size of bins shown by lines in the respective colour).

Table 4: Factors for engine size (ES/M) and frontal area (A/M) contribution. Note that A/M should be in cm^2/kg.

		Petrol	Diesel
ES/M factors	c_1	16.3	9.52
	c_2	-17.3	-11.3
A/M factors	c_1	0.472	1.43
	c_2	-11.0	-28.4

For engine size, the difference between $RWCO_2$ and the predicted value (i.e. $CO_2 - a\,M - b(t) - c_1\,\mathrm{X} - c_2$) for petrol vehicles is (0.0 ± 26.5) g/km, while for diesel the difference between the model and measured data is (0.0 ± 23.0) g/km. Similarly, for frontal area, the difference is (0.1 ± 25.6) g/km and (0.3 ± 22.5) g/km for petrol and diesel respectively. Note that, considering the size of the uncertainties, there is no statistically significant change to the average difference between predicted CO_2 values and $RWCO_2$ because of the addition of these secondary terms.

4 Conclusions

The project 'More Information Less Emissions – Empowering Consumers for a Greener 21st Century' (MILE21) aims to inform consumers with regards to the fuel consumption and emissions of passenger cars in the European market. To do so, an initial model was developed based on basic vehicle properties, in this case mass and build year. This initial model was based on the real-world fuel consumption of diesel, petrol, petrol hybrid, and petrol plug-in hybrid passenger cars.

The real-world fuel consumption of passenger cars was obtained from the Dutch fuel card provider Travelcard Nederland BV. The Travelcard data included data for 900,000 vehicles. A subset of this data is used, which includes petrol and diesel passenger cars with a mass (in running order) less than 2200 kg and a build year of 2009 or later. In this subset there are around 92,000 petrol vehicles, 113,000 diesel vehicles, 9,000 petrol hybrid vehicles (excluding plug-ins), and 2,000 petrol plug-in hybrid vehicles.

The initial Model M1 for real-world fuel consumption is based on a mass-factor term which outlines the mass-dependence of the real-world fuel consumption, as well as build year dependent offset. This build year dependency reflects changes in vehicle technology over time. The initial model has a standard deviation in CO_2 emissions of around 26 g/km for the investigated data set, which may largely be attributed to driver behaviour. The addition of terms to Model M1 based on the power, engine size, and frontal area of the vehicles was also investigated, but did not lead to a statistically significant improvement in the CO_2 prediction. For this reason, they were not included.

This initial model will be expanded in a second model, expected in 2020, which will further analyse the representativeness of Dutch driver behaviour for Europe.

5 References

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6 Signature

The Hague, 27 June 2019

TNO

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A Implementation of Model M1 to approximate real-world CO_2

Essential Vehicle Parameters

Vehicle mass in running order (in kg) Mass in running order is the mass of the empty vehicle plus 100 kg.		(1)
Vehicle type (petrol, diesel, hybrid, plug-in)		(2)
Build year		(3)

Model factors

These can be found in the tables in the text, which have also been reprinted below.

Mass factor $\boldsymbol{a}$ Look up value for vehicle type from Table 1		(5)
Build year factor $\boldsymbol{b}(\boldsymbol{t})$ Look up value for year and vehicle type from Table 2		(6)

Calculation

Mass term Multiply Box (1) by Box (5): $a \times M$		(7)
Approximation CO_2 (g/km) Add Box (6) and Box (7): $a\,M + b(t)$		(8)
Approximation fuel consumption (L/100 km) Divide Box (8) by 23.7 for petrol, or 26.5 for diesel fuel equivalent		(9)

Secondary Contributions

Power (in kW)		(i)
Power/mass Divide (i) by Box (1), then divide by 1000 to get power/mass in kW/tonne		(ii)

If the value (ii) is less than 50, or greater than 90, it is likely that the CO_2 approximation in Box (8) is an underestimation.

An additional contribution due to engine size or frontal area may also be calculated. However, it is unlikely that this significantly improves the CO_2 approximation in Box (8).

Engine size (in cubic centimetre)		(iii)
Frontal area (in cm^2)		(iv)
Engine size/mass Divide (ii) by Box (1)		(v)
Area/mass Divide (iii) by Box (1)		(vi)
Engine size factor c_1 Look up value for fuel from Table 4		(vii)
Engine size factor c_2 Look up value for fuel from Table 4		(viii)
Engine size contribution Multiply (v) by (vii), then add (viii): $c_1 \times \mathrm{X} + c_2$		(ix)
Approximation CO_2 with engine size correction Add Box (8) and (ix): $a\,M + b(t) + c_1\,\mathrm{X} + c_2$		(x)
Frontal area factor c_1 Look up value for fuel from Table 4		(xi)
Frontal area factor c_2 Look up value for fuel from Table 4		(xii)
Frontal area contribution Multiply (iii) by (xi), then add (xii): $c_1 \times \mathrm{X} + c_2$		(xiii)
Approximation CO_2 with Frontal area correction Add Box (8) and (xiii): $a\,M + b(t) + c_1\,\mathrm{X} + c_2$		(xiv)

A.1 Tables reprinted from main text

Table 1: Mass factor *a* for petrol, diesel, petrol hybrid, and petrol plug-in hybrid passenger cars.

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2009	68.9	49.7	97.2	
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2012	54.8	41.1	87.7	-31.1
2013	52.5	38.5	89.2	-28.8
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