Urban transport modelling – An investigation into the effects of urban traffic, speed limits and driving style on travel times, fuel efficiency and CO_2 and NO_x emissions

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Abstract

Urban road transport is remarkably inefficient. Average traffic speeds in London are 7.4mph (11.9km/h) [1] and the costs to run and fuel a car are at an all-time high, yet urban car usage is still staggeringly large. As such, the associated CO_2 and NO_x emissions, traffic deaths and injuries from urban road transport are also unnecessarily large. An innovative model-based approach was used to investigate the effect of maximum vehicle speed, driving style and vehicle size on average journey speeds, CO_2 and NO_x emissions and fuel efficiency in typical urban traffic. The model predictions were validated against experimental data and the model was found to be a good representation of London traffic.

It was found that higher peak vehicle speeds, controlled via model simulated speed limits, adversely affected CO_2 and NO_x emissions, whilst having only a small effect on total journey times. This is because the emissions were dominated by the energy required to accelerate the vehicle in stop-start traffic. This contrasts to many of the accepted models in the literature, which exclude the effect of stop-start traffic and consider only the 'cruise' portion of the journey. For the modelled Ford Focus EcoBoost petrol hatchback, CO_2 emissions at a speed limit of 30mph (48.3km/h) were found to be 22.3% greater than at a speed limit of 20mph (32.3km/h). For the modelled BMW X5 diesel SUV, CO_2 emissions are 37.8% higher at a speed limit of 30mph than at 20mph. The model predicted difference in average journey speed for was only 12.9% greater at 30mph than at 20mph, significantly less than the increase seen in emissions and fuel efficiency. Higher peak speeds were found to have a significantly greater impact of emissions and fuel efficiency than a change in driving styles. An aggressive driving style only resulted in a 7.7% increase in fuel efficiency at 30mph. Vehicle size was also found to impact the emissions and fuel efficiency, with the difference scaling approximately with vehicle mass.

Introduction

The aim of this investigation is to develop a model of the fuel consumption and NO_x and CO_2 emissions for different vehicle types that is representative of real-world driving behaviour, primarily in built-up city traffic. London was used as an example, but this model could also be applied to similarly dense cities where stop/start traffic is the common, rather than cities with a traffic system that is dominated by cross city highways. The NO_x model was based on real-world data from on-road testing using tailpipe Portable Emission Measuring Systems. The CO_2 and fuel efficiencies were based on engine brake specific fuel consumption maps from US Environmental Protection Agency (EPA)

National Vehicle and Fuel Emissions Laboratory and validated experimentally by the authors using a simple test route and the built-in trip computer fuel efficiency measurements.

The existing literature on the relationship between speed and emissions is limited, with many sources incorrectly quoting an optimum speed for maximum fuel efficiency of around 55mph (88.5km/h). We believe this is based on data from 1997 conducted by the Oak Ridge Laboratory [1] which is quoted at https://en.wikipedia.org/wiki/Fuel_economy_in_automobiles, leading to its increased visibility and the public misconception of this holds true for all vehicles. The often-quoted data is presented in Figure 1. This data was captured in the US and as such is measured in miles per US gallon, however, to allow for comparison to the data captured in this investigation, the data has been converted to miles per imperial gallon.

Of note is that the most recent vehicle in the study (the 1997 Toyota Celica) has its highest fuel efficiency at 25mph (40.2km/h). The vehicles with clearly optimal fuel economy at around 55mph (the Oldsmobile Cutlass and the Oldsmobile Olds 88) are typically 3.5L V6 engines coupled to 3 speed automatic gearboxes, a configuration that is not representative of vehicles on the road in Europe in 2022.

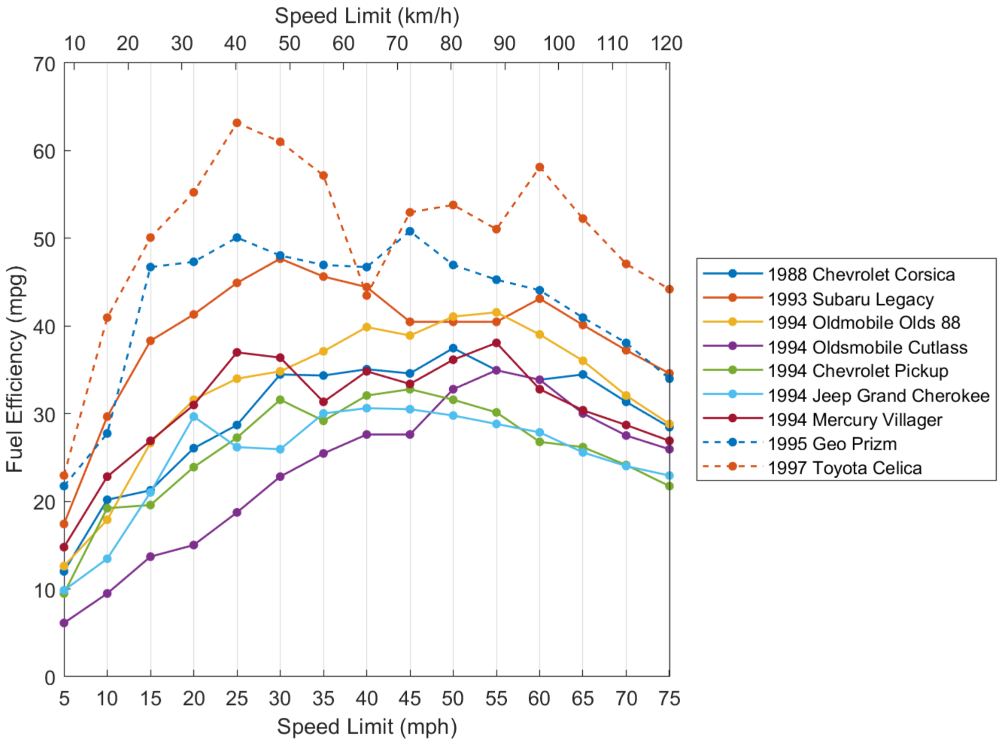

Figure 1. Often quoted, although outdated, data which shows the optimum fuel efficiency of vehicles is often around 55mph [1].

Having validated the model, it was then used to investigate the impact of different speed limits on average speed of travel/travel times and exhaust emissions. Different speed limits were modelled from 10mph (16.1km/h) to 40mph (64.4km/h).

Different driving behaviour was modelled, and this involved modelling different combinations of acceleration and different engine speed thresholds at which the vehicles shift up a gear when accelerating. This allows aggressive driving behaviour to be compared to conservative driving behaviour.

Engines often perform more efficiently when vehicles are travelling at higher speeds, but more energy is initially required to accelerate to these higher speeds. Knowing this, the model was used to investigate the travel distance over which higher speed limits become more efficient than lower speed limits.

Model Details

The model is designed to simulate the driving behaviour, speed, fuel consumption and emissions of vehicles in stop-start traffic that is typical of driving in a busy city. It was modelled on London traffic but would also apply to similar European cities.

The traffic was modelled as a queue of identical vehicles that crossed a series of traffic lights, which each represent hitting a junction, pedestrian crossing, turning vehicle or other obstruction or reason causing the driver to slow down. The spacing of the traffic lights was set to 160m, based on Google Street View observations of a series of large London roads (A23, A2, A315, A219).

A queue of 100 vehicles was modelled driving the route. The 95th vehicle in the queue is assumed to be in fully developed traffic, and it is this vehicle which is analysed in further detail. The vehicles start from stationary and are then modelled to behave in the following ways:

- Slow to a complete stop at red lights
- Slow or continue at amber lights, depending on whether there is safe distance to stop
- Maintain a safe distance from the vehicle in front, and stopping if required
- Shift up to achieve the required torque when accelerating
- Shift up to maintain an efficient engine speed when travelling at a constant speed
- Shift down to maintain the correct gear when decelerating

The simulation is repeated 50 times with different random traffic light phasing. For each vehicle, and for each step of the simulation, the speed and position are calculated based on defined driving characteristics. From this, the energy required to travel the previous calculated distance is calculated. The energy required is a combination of rolling and air resistances and force required to accelerate. The transmission of the vehicle is modelled, allowing the vehicle speed and energy required to move to be translated into a gear, engine speed and required torque. Using engine brake specific fuel consumption (BSFC) maps from the US Environmental Protection Agency (EPA) [2] [3] [4], the fuel consumption rate of the engine is determined from the engine speed and required torque. Fuel consumption and CO_2 emissions can be calculated from this. NO_x emissions are calculated from a similar engine map created from real-world data.

The number of stop-starts is different for each simulation, due to the random phasing of the traffic lights. Transport for London (TfL) published data shows that the average speed in London traffic is 7.4mph (11.9km/h) [5]. The traffic light duty cycle was adjusted to give an average journey speed of 7.4mph with a 25mph (40.2km/h) speed limit, with this being representative of a mix of the 20mph (32.2km/h) and 30mph (48.3km/h) speed limits that are typical across London. The traffic light duty cycle was set to 70%, meaning that the lights were on red for 70% of the time, and green for 30%.

The model runs over a distance of 4km, but the time taken, energy consumed and vehicles emissions over the initial 640m (4 sets of traffic lights) are ignored. This is to allow the vehicles time to reach a regular flow of traffic, removing the impact of the initial conditions.

Vehicle Velocity

The model allows a vehicle to accelerate if the gap to the vehicle in front increases beyond 3m (8m front bumper to front bumper for a 5m long vehicle). The vehicle then begins to accelerate according to Eq. 1, where is v the velocity (m/s), a is the acceleration (m/s^2), Δt is the duration of the model time step (s), n indicates the current time step and $n-1$ indicates the previous time step.

$$v_n = v_{n-1} + a_n \Delta t \qquad \text{Eq. 1}$$

The vehicle accelerates until it reaches the designated speed limit. Once at the speed limit it maintains a constant velocity until it needs to slow down due to a red light or a slowing car.

A stopping distance for each vehicle at their current velocity is calculated. This is based on rule 126 of the UK Highway Code [6] which gives a general guide for stopping distances at different velocities. This stopping distance accounts for braking distance and the thinking distance, which accounts for the driver's reactions time to a situation which requires them to stop.

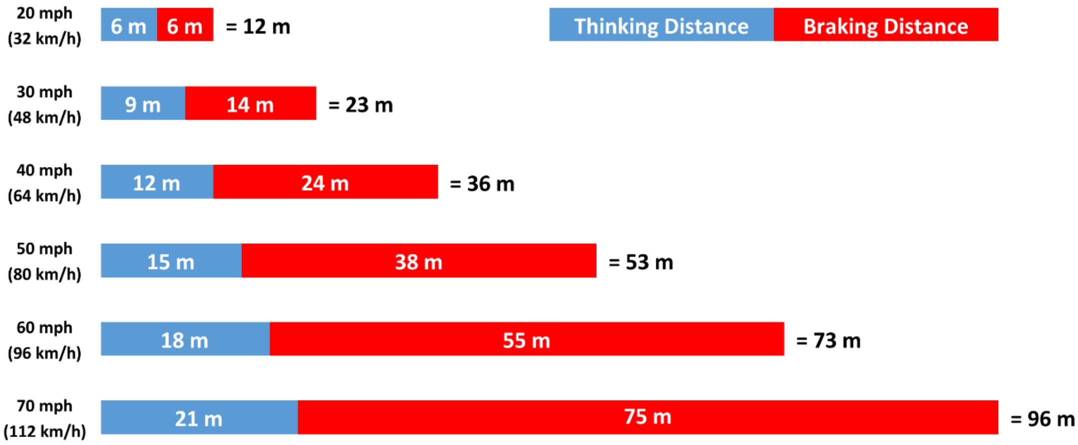

Figure 2. Stopping distance guide for a vehicle according to rule 126 of the UK Highway Code [6].

If a vehicle is approaching a red light without another vehicle in front of it, then it slows according to Eq. 2, where v_{start} is the velocity at which the vehicle begins to slow down (m/s), $d_{to\ lights}$ is the vehicle's current distance to the lights (m), $d_{stopping}$ is the stopping distance (m) linearly interpolated from stopping distances in Figure 2, and $d_{margin\ to\ lights}$ is the distance from the lights at which the vehicle will come to a stop (m), which was set as 1m:

$$v_n = \min\left(v_{n-1}, \left(v_{start}\left(\frac{d_{to\ lights} - d_{margin\ to\ lights}}{d_{stopping} - d_{margin\ to\ lights}}\right)\right) + \left(\frac{2}{2.24}\right)\right) \qquad \text{Eq. 2}$$

The (2/2.4) term makes it so that the vehicle will be at approximately 2mph (3.2km/h) when it reaches $d_{margin\ to\ lights}$. Once the vehicle reaches 2mph, it's velocity is instantly reduced to 0mph. This prevents the vehicle from asymptotically approaching the lights.

If the traffic light is about to change to red and the stopping distance for the vehicle at its current velocity is less than the distance to the lights, then the vehicle cannot safely slow in time for the lights. Instead, the vehicle will not slow down and will instead carry on through the lights. This is to simulate the amber phase of the traffic lights.

A vehicle will start to slow down if it approaches another slowing vehicle. This occurs once the distance to the vehicle in front, $d_{to\ car\ in\ front}$ (m), gets within the 3m + $d_{stop\ gap}$, and when this distance is reducing. $d_{stop\ gap}$ is the gap that the cars maintain to one another when stopped (m), which was set to 7m. When this happens, the vehicle behind begins to slow down to the speed of the vehicle in front. As the happens, the gap between the vehicles reduces to the stop gap. The vehicle slows down in accordance with Eq. 3, where $v_{car\ in\ front}$ is the velocity of the car immediately in front of the vehicle in question (m/s):

$$v_n = \max\left(v_{car\ in\ front}, min\left(v_{n-1}, v_{car\ in\ front} + \max(0, v_{n-1} - v_{car\ in\ front})\left(\frac{d_{to\ car\ in\ front} - d_{stop\ gap}}{3}\right)\right)\right) \quad \text{Eq. 3}$$

Vehicle Position

Knowing the velocity of the vehicle allows the distance travelled over the current time step to be calculated from Eq. 4, where x is the vehicle position relative to a common start point (m):

$$x_n = x_{n-1} + v_n \Delta t \quad \text{Eq. 4}$$

Required Force to Move

At each time step, the force required to achieve the velocity previously calculated is determined. The force to overcome the air resistance is calculated from Eq. 5, where F_d is the drag force (N), c_d is the coefficient of drag for the vehicle, ρ is the density of air (kg/m^3) and A is the characteristic frontal area of the vehicle (m^2):

$$F_d = \frac{c_d \rho v_n^2 A}{2} \quad \text{Eq. 5}$$

The force to overcome the rolling resistance can be estimated from Eq. 6. This equation has been correlated specifically for use with air filled car tyres on dry roads. Here, F_r is the rolling resistance (N), p is the tyre pressure (bar), m is the mass of the vehicle (kg) and a_g is acceleration due to gravity (m/s^2).

$$F_r = \left(0.005 + \left(\frac{1}{p}\right)\left(0.01 + 0.0095\left(\frac{v}{360}\right)^2\right)\right) m a_g \quad \text{Eq. 6}$$

If the vehicle is at a constant velocity, then the force required to maintain that velocity is the force required to overcome the air resistance and rolling resistance being experienced by the vehicle, as per Eq. 7.

$$F = F_d + F_r \quad \text{Eq. 7}$$

If the vehicle is accelerating, then the then the force required to accelerate, F_a (N) must also be accounted for. This is calculated using Eq. 8.

$$F_a = m a_n \quad \text{Eq. 8}$$

For a vehicle that is accelerating rather than travelling at a constant velocity, the force required is the sum of these 3 forces, as shown in Eq. 9.

$$F = F_d + F_r + F_a \qquad \text{Eq. 9}$$

Vehicle Transmission

Knowing the vehicle velocity and the characteristics of the vehicle's drivetrain allows the engine speed to be calculated. The vehicle's all start in first gear and shift up a gear when their engine speed goes above a defined threshold for that vehicle. There are 2 different thresholds for shifting up a gear. If the vehicle is still accelerating, then it will shift up when it exceeds the upper up-shift threshold. If the vehicle is not accelerating (i.e. it has reached the speed limit), then it will shift up when it exceed the lower up-shift threshold. The upper up-shift threshold allows the vehicle to utilise more engine torque when required for acceleration. The vehicle will shift down a gear when its engine speed drops below the defined down-shift threshold. These thresholds are summarised in Table 1 and Table 2 for the simulated petrol and diesel vehicles respectively. The petrol vehicle shift thresholds are slightly higher than those of the diesel to reflect how these vehicles are driven in practice.

Table 1. Engine speed thresholds at which the simulated petrol engine vehicles shift gear.

	Engine Speed Threshold
Shift up when accelerating	2250 RPM
Shift up when not accelerating	1800 RPM
Shift down	1000 RPM

Table 2. Engine speed thresholds at which the simulated diesel engine vehicles shifts gear.

	Engine Speed Threshold
Shift up when accelerating	2000 RPM
Shift up when not accelerating	1500 RPM
Shift down	1000 RPM

With the current gear known, the engine speed is calculated from Eq. 10, where ω_{RPM} is the engine speed (RPM), GR is the gear ratio of the current gear, FD is the final drive ratio of the transmission and r is the radius of the wheel (m):

$$\omega_{RPM} = v\ GR\ FD \left(\frac{60}{2\pi r}\right) \qquad \text{Eq. 10}$$

Required Energy to Move

The power required, P (W), is calculated from Eq. 11. The power is calculated from the force required to move, the vehicle velocity and the overall efficiency of the vehicle, η, which is assumed to be 0.9 to account for drivetrain loses.

$$P = \frac{F v_n}{\eta} \qquad \text{Eq. 11}$$

From this power and the engine speed, the torque, T (Nm), required from the engine is calculated using Eq. 12.

$$T = P\left(\frac{60}{2\pi\omega_{RPM}}\right) \qquad \text{Eq. 12}$$

With a known engine speed and required torque, the fuel consumption rate can be determined by interpolating the engine's brake specific fuel consumption (BSFC) map. For the simulated Ford Focus in this investigation, a 2013 Ford 1.6l EcoBoost engine [2] model was used. The BSFC map allows the fuel consumption rate of the engine to be determined for a combination of engine speed and torque. Similar BSFC maps were used to model the engines of the other vehicles simulated in this investigation. The BSFC map for a the 1.6l Ford EcoBoost used can be seen in Figure 3.

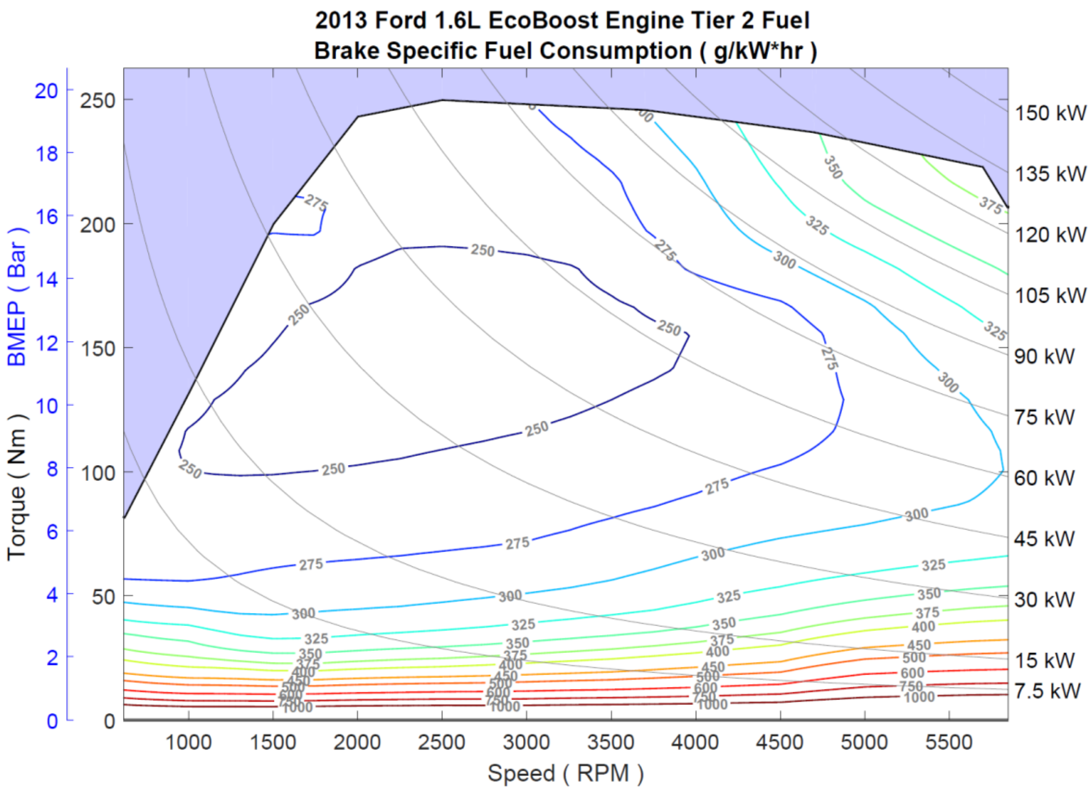

Figure 3. Brake Specific Fuel Consumption map for the 2013 Ford 1.6l EcoBoost Engine [2].

If the required torque and current engine speed is unachievable (i.e. it is outside the bounds of the BSFC map) then the vehicle shifts down a gear, resulting in a higher engine speed and lower torque. If the required torque and engine speed are still unachievable, then the vehicle will continue to shift down gears until it is achievable.

From the fuel consumption rate, f (l/s), the energy consumed, E (J), can be calculated from Eq. 13 using the calorific value of petrol, E_{pet} (34.6x10^6 J/l). For diesel engine vehicles, the calorific value of diesel is used instead (38.8x10^6 J/l).

$$E = fE_{pet}\Delta t \qquad \text{Eq. 13}$$

If the vehicle is idling rather than moving, the energy is calculated from Eq. 14, where V_{eng} is the engine capacity (l) and f_{idle} is the idling fuel consumption rate, normalised as the volume of petrol consumed per second per unit volume of engine capacity (1/s). This assumes the vehicle does not have stop-start technology that stops the engine when vehicle is stationary. A rate of 0.2l/hr of fuel when idling was used.

$$E = E_{pet}V_{eng}f_{idle}\Delta t \qquad \text{Eq. 14}$$

The energy used throughout the journey is the sum of the energy used at each time step as calculated from the equations above.

CO_2 Emissions

CO_2 emissions are directly proportional to fuel consumption. Fuel consumption is known from the fuel consumption rate previously determined. 2392g of CO_2 is produced per litre of petrol burned, such that the average CO_2 emissions (g/km) can be calculated from Eq. 15, where V_{pet} is the volume of petrol (l) and d_{total} is the total distance travelled by the vehicle over the journey (m):

$$CO_2 = \frac{2392 * \frac{E_{total}}{E_{pet}}}{d_{total}} \tag{Eq. 15}$$

For diesel engine vehicles, 2640g of CO_2 is produced per litre of fuel burned, such that Eq. 16 is used instead.

$$CO_2 = \frac{2640 * \frac{E_{total}}{E_{diesel}}}{d_{total}} \tag{Eq. 16}$$

NO_x Emissions

A map of NO_x emissions as a function of engine speed and required torque was produced from real-world data for a Ford Focus supplied by Emissions Analytics. A vehicle was fitted with telemetry equipment and sensors to measure exhaust composition in real-time. This vehicle was driven over a distance of approximately 185km and data logged throughout at a rate of 1 sample per second.

Approximately 10,000 data points were recorded and can be seen in Figure 4 below. The vehicle stayed below an engine speed of 2500 RPM throughout the tests, and typically stayed below an engine speed of 2250 RPM.

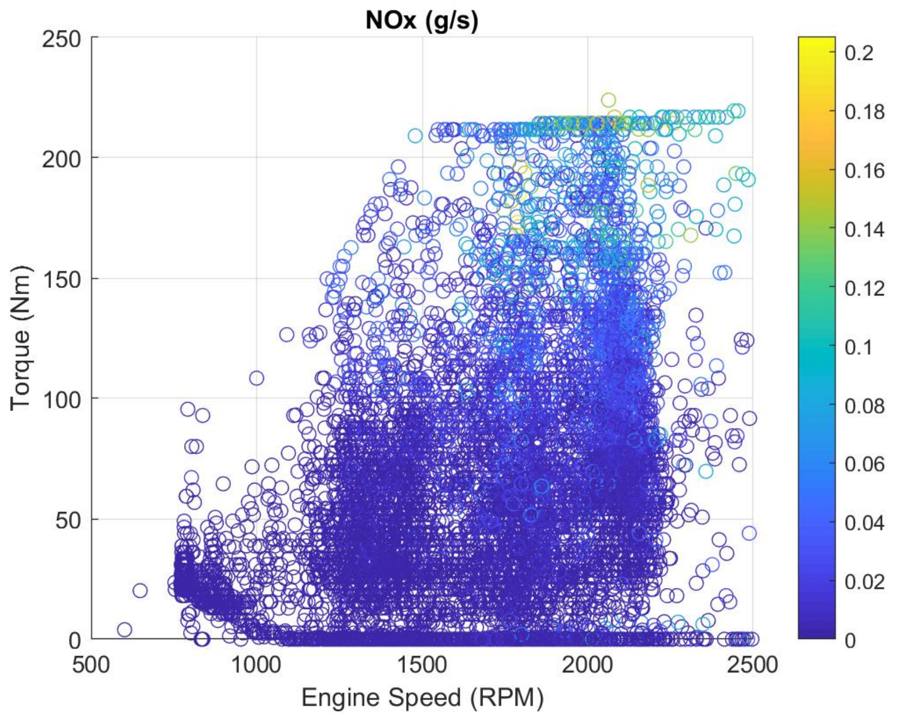

Figure 4. Real world NO_x emissions for a Ford Focus as a function of engine speed and supplied torque.

This data needs to be smoothed into a usable map before it can be applied to the model. The range of engine speeds and supplied torque values were divided into bins into which these data points were sorted. The mean value of each bin was calculated, resulting in the plot in Figure 5.

Some bins are unpopulated, so a moving average, with an averaging window size of 4, was used to approximate the missing mean NO_x values. The moving average was first applied in the engine speed direction, then in the torque direction. This resulted in the map seen in Figure 6.

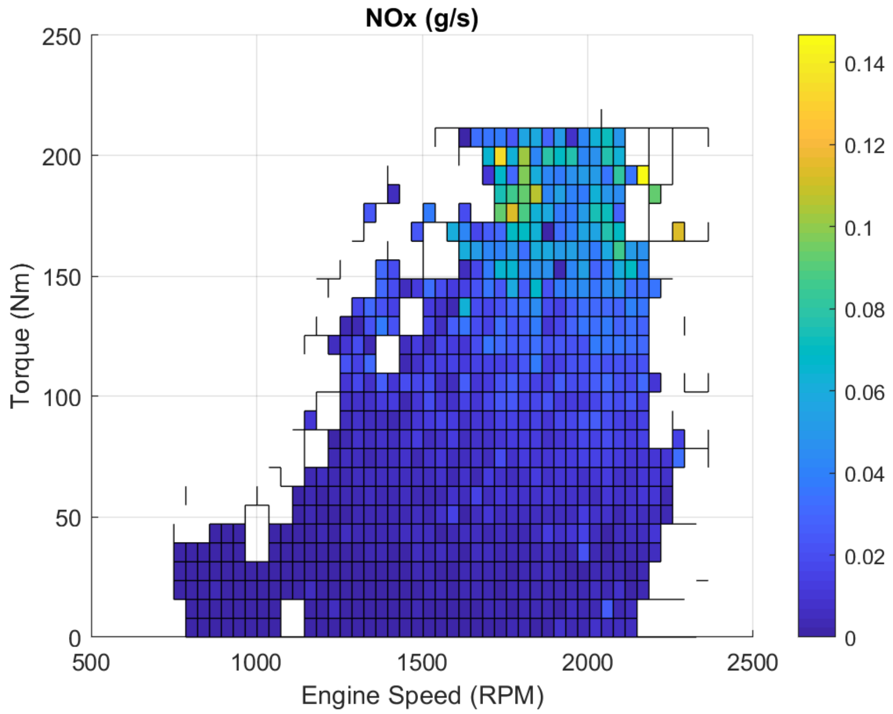

Figure 5. Mean NO_x value for each bin.

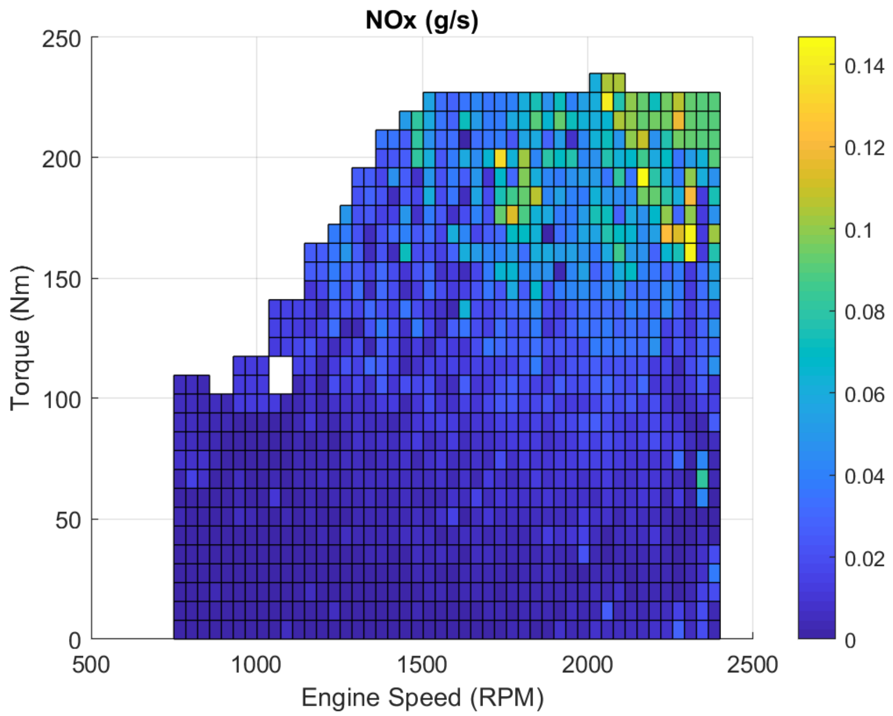

Figure 6. Mean NO_x map with missing data approximated using a moving average over a window size of 4 data points.

A moving average with a window size of 7 is then applied across the entire map to smooth it into something more usable. The moving average was first applied in the engine speed direction, then in the torque direction. This results in the smooth map seen in Figure 7.

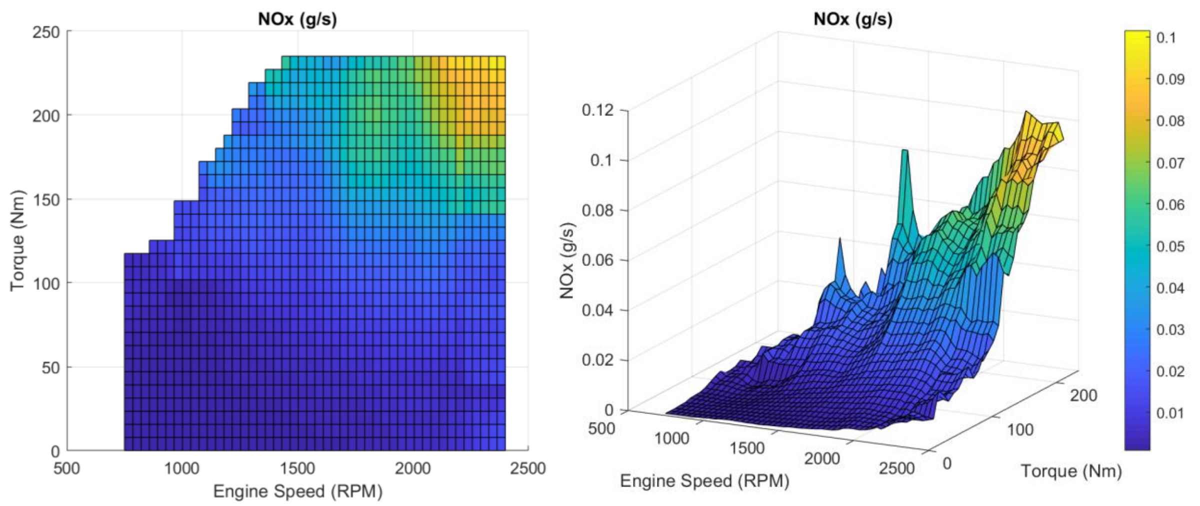

Figure 7. Final averaged NOx map.

Vehicle Characteristics

The available Ford EcoBoost engine BSFC map [2] is only applicable to a petrol engine vehicle, whereas the NO_x emissions map is only applicable to a diesel engine vehicle. Using this data and the vehicle characteristics in Table 3 and Table 4, it was possible to model two similar, highly comparable vehicles – a petrol engine 2016 Ford Focus 1.5 EcoBoost for predicting CO_2 emissions, and a diesel engine 2016 Ford Focus 1.5 TDCi for predicting NO_x emissions.

Table 3. Vehicle specification for 2016 Ford Focus 1.5 EcoBoost (Petrol) [7].

Vehicle mass, m	1250 kg
Coefficient of Drag, C_d	0.31
Frontal Area, A	2.25 m^2
Engine Capacity, V_{eng}	1.499 l
Tyre Pressure, p	2.14 bar
Wheel Radius, r	0.203 m
Gear Ratios, GR	[3.727, 2.048, 1.357, 1.032, 0.821, 0.69]
Final Drive Ratio, FD	4.067

Table 4. Vehicle specification for 2016 Ford Focus 1.5 TDCi (Diesel) [8].

Vehicle mass, m	1268 kg
Coefficient of Drag, C_d	0.31
Frontal Area, A	2.25 m^2
Engine Capacity, V_{eng}	1.499 l
Tyre Pressure, p	2.14 bar
Wheel Radius, r	0.203 m
Gear Ratios, GR	[3.727, 2.048, 1.258, 0.919, 0.738, 0.622]
Final Drive Ratio, FD	3.611

Further simulations were completed to investigation the impact of vehicle size on exhaust emissions and fuel efficiency under urban traffic conditions. Sports Utility Vehicles (SUV) have been increasing in popularity in recent years despite these vehicles not being ideal for travel in busy city traffic. As such, a 2016 Mazda CX-9 was modelled. This is a petrol engine SUV, similar in size and mass to other popular SUVs such as the Range Rover Discovery, allowing for a comparison to the petrol engine

Ford Focus. This vehicle uses a 2.5l Mazda Skyactiv engine [3]. The vehicle characteristics for this vehicle are in Table 5.

Table 5. Vehicle specification for 2016 Mazda CX-9 (Petrol) [9].

Vehicle mass, m	1951 kg
Coefficient of Drag, C_d	0.35
Frontal Area, A	2.86 m^2
Engine Capacity, V_{eng}	2.488 l
Tyre Pressure, p	2.14 bar
Wheel Radius, r	0.254 m
Gear Ratios, GR	[3.487, 1.992, 1.449, 1, 0.707, 0.6]
Final Drive Ratio, FD	4.411

Additionally, a diesel engine SUV was also modelled. A 2015 BMW X5 was chosen as this is of a similar mass and size to the Mazda CX-9, allowing for a good comparison of petrol and diesel efficiency. This vehicle uses a 3.0l BMW N57 engine [4] and its characteristics are summarised in Table 6.

Table 6. Vehicle specification for 2015 BMW X5 (Diesel) [10].

Vehicle mass, m	2070 kg
Coefficient of Drag, C_d	0.88
Frontal Area, A	2.84 m^2
Engine Capacity, V_{eng}	2.993 l
Tyre Pressure, p	2.14 bar
Wheel Radius, r	0.229 m
Gear Ratios, GR	[4.714, 3.143, 2.106, 1.667, 1.285, 1, 0.839, 0.667]
Final Drive Ratio, FD	3.154

Model Validation

Real-World Data

The model predictions were validated using the telemetry and emissions data captured by Emissions Analytics for a 2016 Ford Focus TDCi. This data was also used to build the NO_x emissions map used in the model. Instead of using the model to calculate position and velocity, the real-world data was used. The model then calculated the energy required to achieve this motion. Using the required energy, vehicle transmission model, engine BSFC map and NO_x emissions map, the emissions that would be created over the simulated equivalent real-world journey were determined.

The model predicted and real-world NO_x emissions can be seen in Figure 8 and Figure 9 as a function of distance covered and time elapsed respectively. The total real-world NO_x emissions of 126g are 24% higher than the model predicted NO_x emissions of 102g. The real-world NO_x emissions have several significant step increases in value which do not coincide with any particular events in the model vehicle velocity. These steps account for much of the difference in the total NO_x emissions. Without these steps, the real-world NO_x emissions would be approximately 96g, making the total model predicted NO_x emissions approximately 6% greater than those of the real-world data.

The emissions are relatively linear as function of distance covered. This is because emissions in both the real-world and model predictions are negligible when the vehicle is stationary. The emissions as a function of time show more variable rates, due the varying speed of the vehicle over the journey.

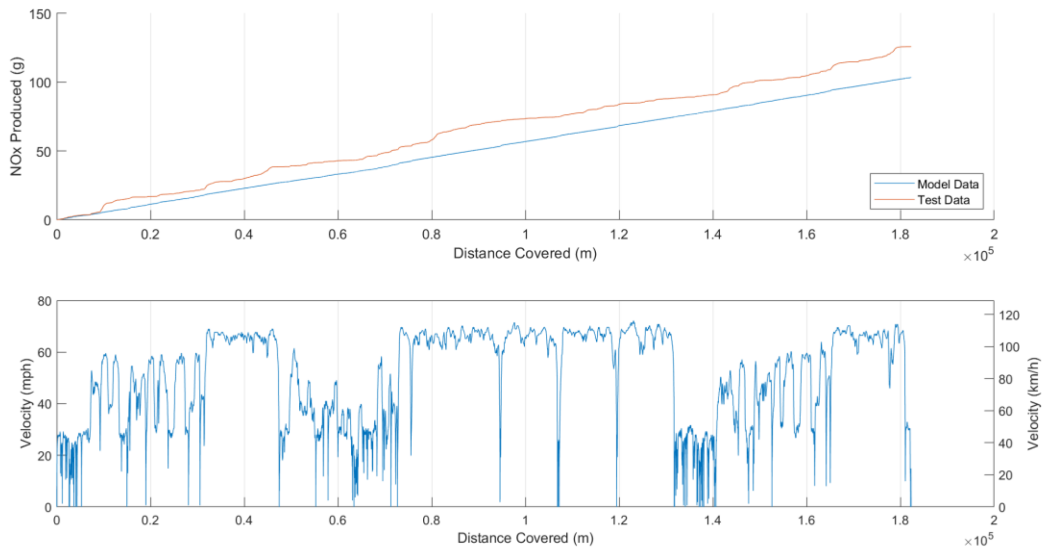

Figure 8. Real-world diesel NO_x emissions vs model predicted diesel NO_x emissions plotted as a function of distance covered.

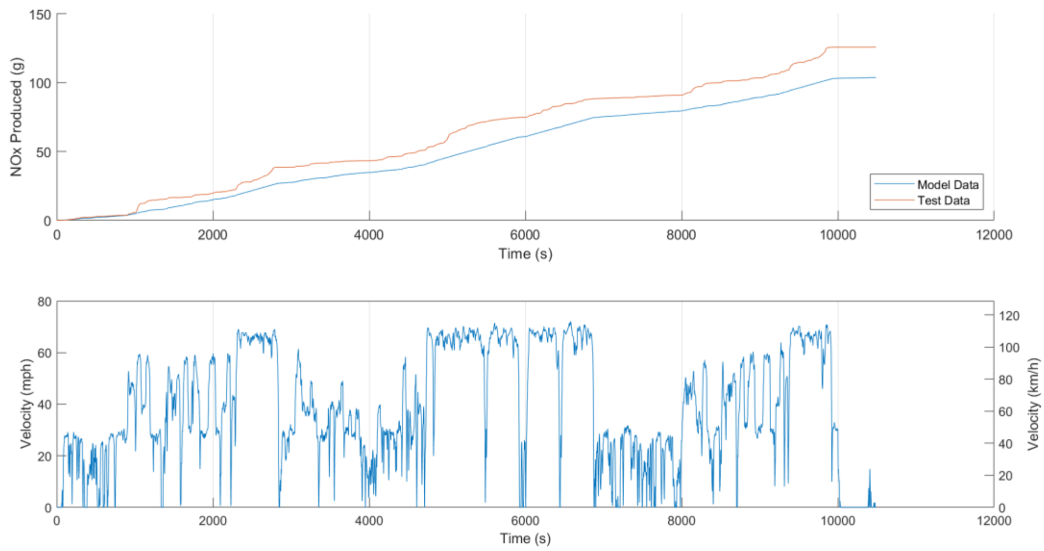

Figure 9. Real-world diesel NOx emissions vs model predicted diesel NOx emissions plotted as a function of elapsed time.

The real-world data is for a diesel engine Ford Focus, and as such the petrol engine model from which the CO_2 emissions are predicted will be slightly different. The vehicle characteristics, except for the engine and transmission, are similar enough that some validation can be made by comparing the model predicted and real-world emissions. The model predicted and real-world CO_2 emissions can be seen in Figure 10 and Figure 11 as a function of distance covered and time elapsed respectively.

The predicted CO_2 emissions agree reasonably well with the real-world data, with the total predicted CO_2 emissions over the journey of 31.0kg being approximately 16% greater than the total real-world CO_2 emissions of 26.7kg. The real-world emissions are initially higher than that of the predictions, perhaps due to the engine being more inefficient when starting cold, which is not accounted for in the model. Despite this, the model predicted CO_2 emissions are greater by the end of the journey, showing that the average model CO_2 emissions rate is slightly greater than that of the real-world.

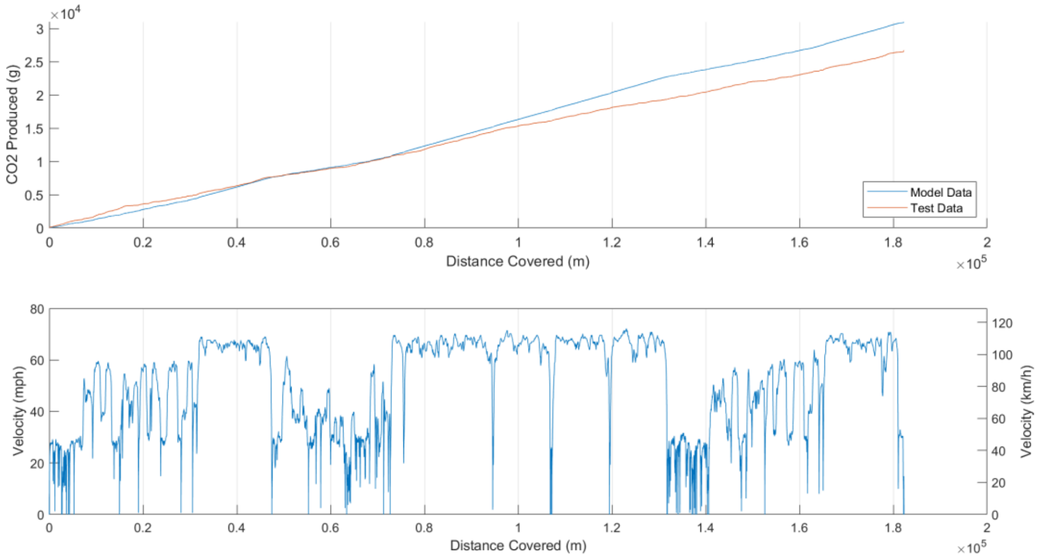

Figure 10. Real-world diesel CO2 emissions vs model predicted petrol CO2 emissions plotted as a function of distance covered.

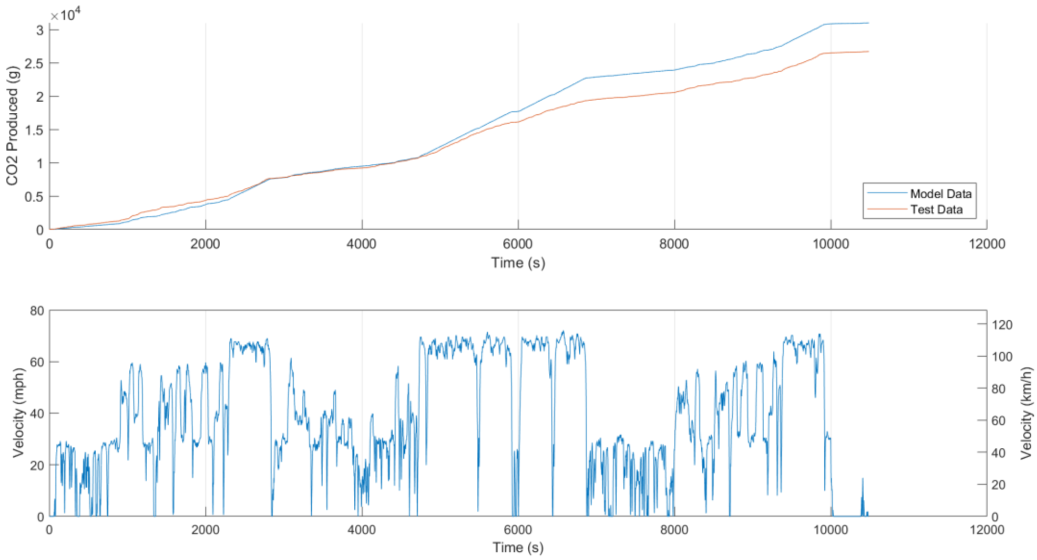

Figure 11. Real-world diesel CO_2 emissions vs model predicted petrol CO_2 emissions plotted as a function of elapsed time.

Results

Cruising at Speed Limit Simulation

It is often assumed that a vehicle is more efficient at higher speeds, typically 55mph, with references often being made to the outdated research carried out by Oak Ridge Laboratory [1], and this is often true because the engine speed and torque required to drive at higher speeds may fall into a more efficient part of the brake specific fuel consumption map. However, such assumptions do not take into account the additional energy required to accelerate up to these higher speeds. This investigation seeks to clarify this misconception by accounting for the acceleration period when discussing efficiency at different speeds.

The energy required to accelerate and cruise at different speed limits was simulated. In these simulations, the vehicles accelerate from stationary up to the speed limit and then continue at constant speed for 25km. The energy required was calculated at each simulation step for different speed limits between 20mph (32.2km/h) and 70mph (112.7km/h) and for an acceleration rate of 1.2 m/s^2.

Higher speed limits required considerably more energy to achieve, as can be seen from Table 7. This table shows that more than twice as much energy is required to accelerate up to 30mph (48.3km/h) than is required to accelerate up to 20mph (32.2km/h). It was also found that travelling at a constant speed of 20mph requires more energy per unit distance travelled than travelling at 30mph. Therefore, after a certain distance has been travelled without any additional periods of acceleration or decelerations, it would be more energy efficient to travel at 30mph rather than 20mph. for these speeds, this distance is 0.48km, and this efficiency cross-over distance also occurs at other speeds, as shown in Table 8 and Figure 12. In built-up areas, particularly in periods of heavy traffic, it is often not possible to travel greater than 0.48km without having to slow or come to a stop, and in these cases, it is always more efficient to travel at 20mph than at 30mph.

Table 7. Energy required to accelerate to different speeds at a rate of 1.2m/s^2 for the simulated 2016 Ford Focus EcoBoost.

Speed limit	**Energy required to accelerate to speed limit**	**Energy relative to energy required to accelerate to 20mph**
20 mph (32.2 km/h)	$2.1x10^5$ J	-
25 mph (40.2 km/h)	$3.1x10^5$ J	148%
30 mph (48.3 km/h)	$4.4x10^5$ J	210%
35 mph (56.3 km/h)	$6.0x10^5$ J	286%
40 mph (64.4 km/h)	$7.8x10^5$ J	371%
45 mph (72.4 km/h)	$9.9x10^5$ J	471%
50 mph (80.5 km/h)	$1.24x10^6$ J	590%

Table 8. Travel distance required for different speed limits to be more efficient than travelling at 20mph (32.2km/h) for the simulated 2016 Ford Focus EcoBoost.

Speed limit	**Distance after which more efficient than 20mph (32.2km/h)**
22.5mph (36.2 km/h)	0.17 km
25 mph (40.2 km/h)	0.34 km
27.5 mph (44.3 km/h)	0.34 km
30 mph (48.3 km/h)	0.48 km
32.5 mph (52.3 km/h)	0.65 km
35 mph (56.3 km/h)	0.84 km
37.5 mph (60.4 km/h)	1.13 km
40 mph (64.4 km/h)	1.61 km
42.5 mph (68.4 km/h)	2.39 km
45mph (72.4 km/h)	3.78 km

Some speeds will continue to diverge over distance, such as 20mph (32.2km/h) and 50mph (80.5km/h). It is more inefficient to cruise at 50mph than at 20mph, and much more inefficient to accelerate to 50mph than to 20mph, such that regardless of distance it will always be more efficient to travel at 20mph. The difference in efficiencies is due to how the engine map is designed and the increased aerodynamic and rolling resistance at higher speeds. This also holds true for more common speed difference such as it always being more efficient to travel at 30mph (48.3km/h) than at 40mph (64.4km/h).

The same simulations were also completed with the 2016 Mazda CX-9 and the 2015 BMW X5. The Mazda CX-9 becomes more efficient at 30mph (48.3km/h) rather than 20mph (32.2km/h) after

1.23km, which is very unlikely to be achieved in urban traffic conditions. Unlike for the Mazda CX-9 and Ford Focus EcoBoost, the BMW X-5 was most efficient for a cruising speed of 20mph, such that it was never more efficient to travel at higher speeds, regardless of distance travelled.

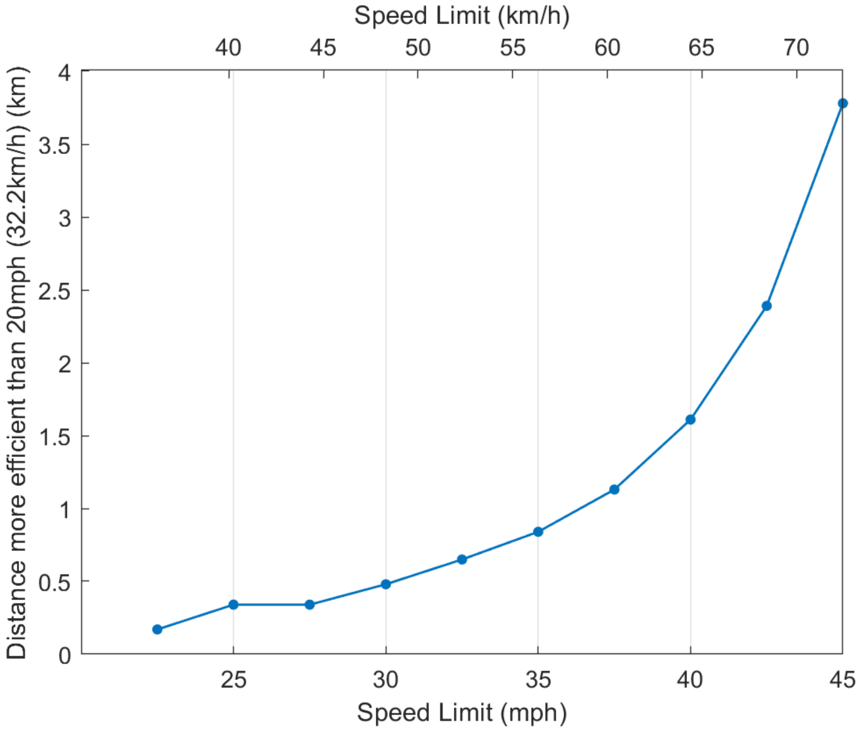

Figure 12. Travel distance required for different speed limits to be more efficient than travelling at 20mph (32.2km/h) for the simulated Ford Focus EcoBoost.

Urban Traffic Simulation

Traffic flow was simulated for the Ford Focus EcoBoost and Ford Focus TDCi vehicles at an acceleration of 1.2m/s^2 and using the engine speed thresholds in Table 1 and Table 2. Speed limits between 10mph (16.1km/h) and 40mph (64.4km/h), in increments of 2.5mph (4.0km/h), were simulated. These simulations were completed at 50 different traffic light timings and the results averaged.

Figure 13 shows the average time taken to travel 3km and Figure 14 shows the average speed of travel derived from this. It can be seen that there is little improvement in travel time and average speed when the speed limit increases above 30mph (48.3km/h). At a speed limit of 40mph (64.4km/h), the average travel speed is only 2.7% greater than at a speed limit of 30mph. The improvements in average speed of travel are greater at speed limits below 30mph. At a speed limit of 30mph, the average travel speed is 12.9% greater than at a speed limit of 20mph (32.2km/h).

Transport for London (TfL) published data shows that the average speed of travel in London, which is made up of a mix of 20mph (32.2km/h) and 30mph (48.3km/h) speed limit zones, is approximately 7.4mph (11.9km/h) [5]. At a speed limit of 25mph (40.2km/h), which could act as a simple approximation of a mix of 20mph and 30mph speed limits, the model simulated vehicles have an average speed of travel of 7.43mph (11.96km/h), which shows this model is representative of traffic in cities like London.

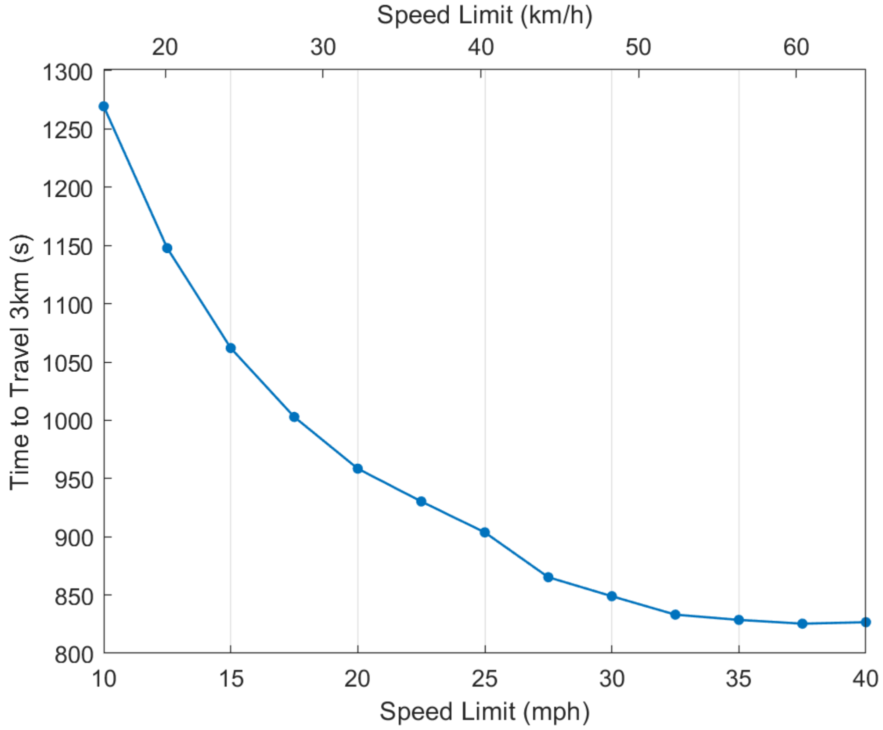

Figure 13. Average travel time of the simulated Ford Focus EcoBoost/TDCi over 3km for different speed limits.

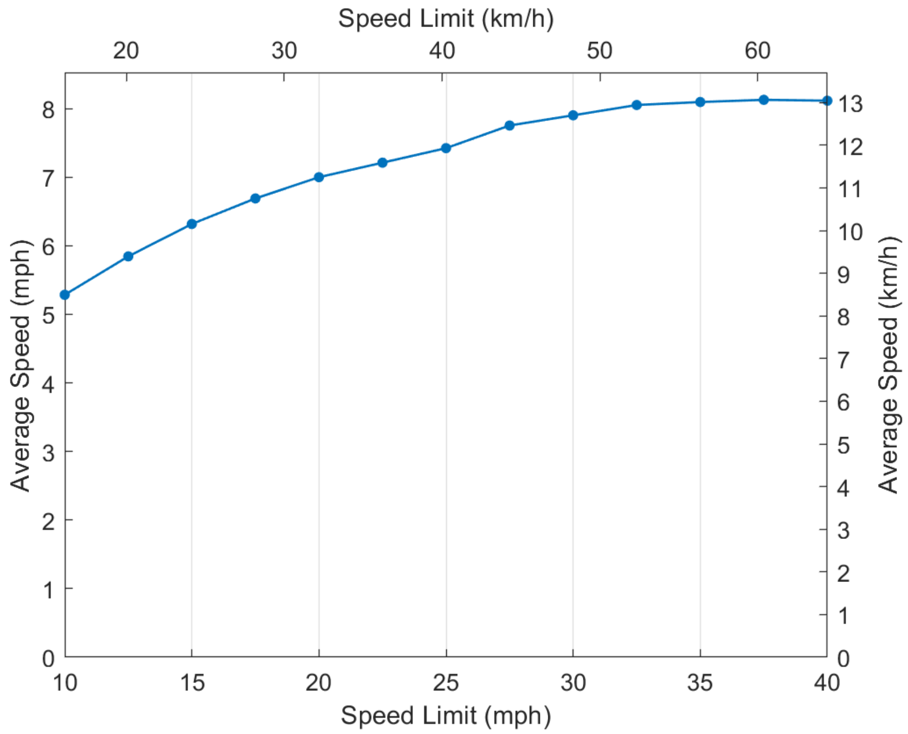

Figure 14. Average speed of the simulated Ford Focus EcoBoost/TDCi for different speed limits.

Figure 15 shows the CO_2 emissions and energy required for the simulated Ford Focus EcoBoost, whilst Figure 16 shows how this translate to fuel efficiency. The data below 20mph (32.2km/h) can be seen to somewhat sawtooth. This is because the narrow speed limit intervals means that some of these points share the same choice of gear at which the vehicle cruises. For example, when travelling at 17.5mph (28.2km/h) or 20mph the vehicle is in 3rd gear, but at 15mph (24.1km/h) the vehicle is still in 2nd gear. The corresponding point on the BSFC map for the engine speed and torque required to cruise at 15mph in 2nd gear is noticeably more inefficient than that required to cruise at 17.5mph in 3rd gear.

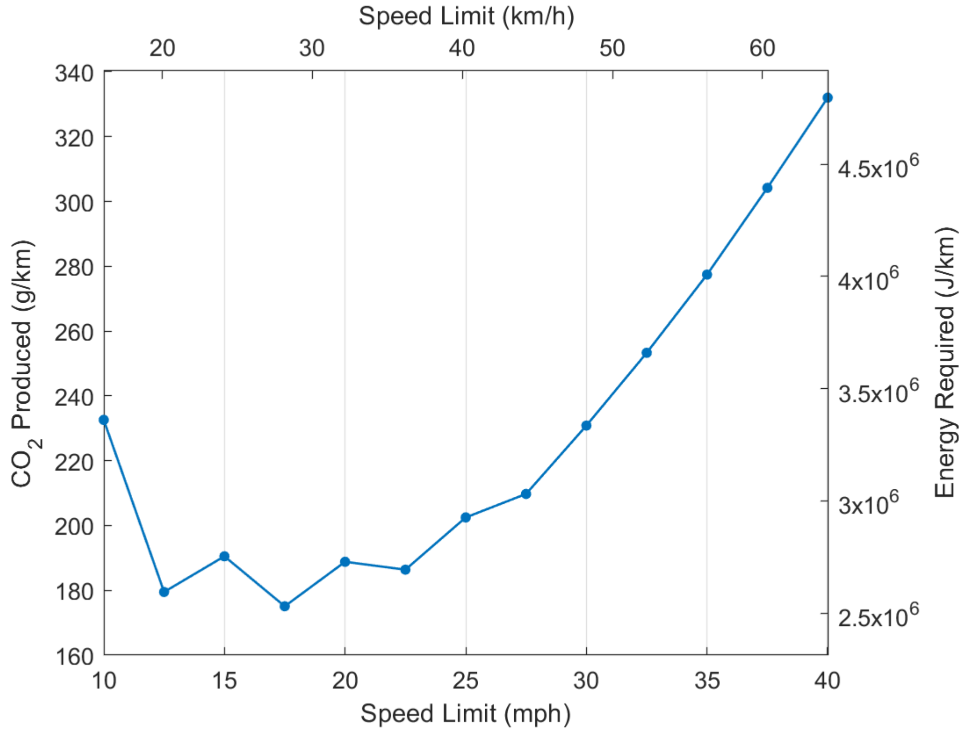

Figure 15. CO2 emissions and energy required per kilometre travelled for a simulated 2016 Ford Focus EcoBoost.

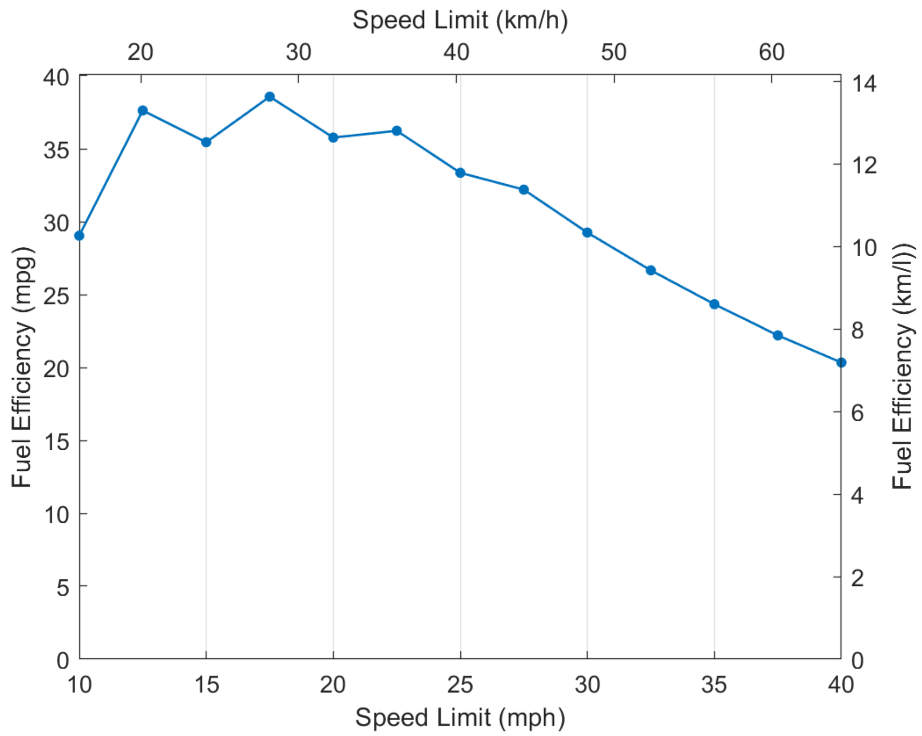

Figure 16. Fuel efficiency under urban traffic conditions for a simulated 2016 Ford Focus EcoBoost.

The energy required and CO_2 emissions can be seen to sharply increase with speed limits above 20mph (32.2km/h). Travelling at a speed limit of 30mph (48.3km/h) results in 22.3% more CO_2 emissions than travelling at a speed limit of 20mph, although Figure 14 shows that this only results in a 12.9% increase in average speed of travel. Travelling at a speed limit of 40mph (64.4km/h) results in a significantly greater 75.9% increase in CO_2 emissions relative to a speed limit of 20mph, for only a 15.9% increase in average speed of travel. This shows that under these dense, urban traffic conditions, there is little benefit in terms of average speed of travel at speed limits of 30mph and 40mph and a significant detriment in terms of increased CO_2 emissions and petrol consumption. Speed limits below 20mph do not result in any significant difference in CO_2 emissions but do results in considerably lower average speeds of travel.

The NO_x emissions from the simulated Ford Focus TDCi are shown in Figure 17. The NO_x emissions exhibit a similar relationship to speed limit as the CO_2 emissions in Figure 15, with little difference below 20mph (32.2km/h), and a sharp increase at speed limits above 20mph, although the increase in NO_x emissions above 20mph is significantly greater than the increase in CO_2 emissions. Travelling at a speed limit of 30mph (48.3km/h) results in 40.6% more NO_x emissions than travelling at a speed limit of 20mph, whilst travelling at a speed limit of 40mph (64.4km/h) results in 150.0% more NO_x emissions relative to a speed limit of 20mph. Again, this shows that under these conditions, there is little benefit in terms of average speed of travel at speed limits of 30mph and 40mph and a significant detriment in terms of increased NO_x emissions.

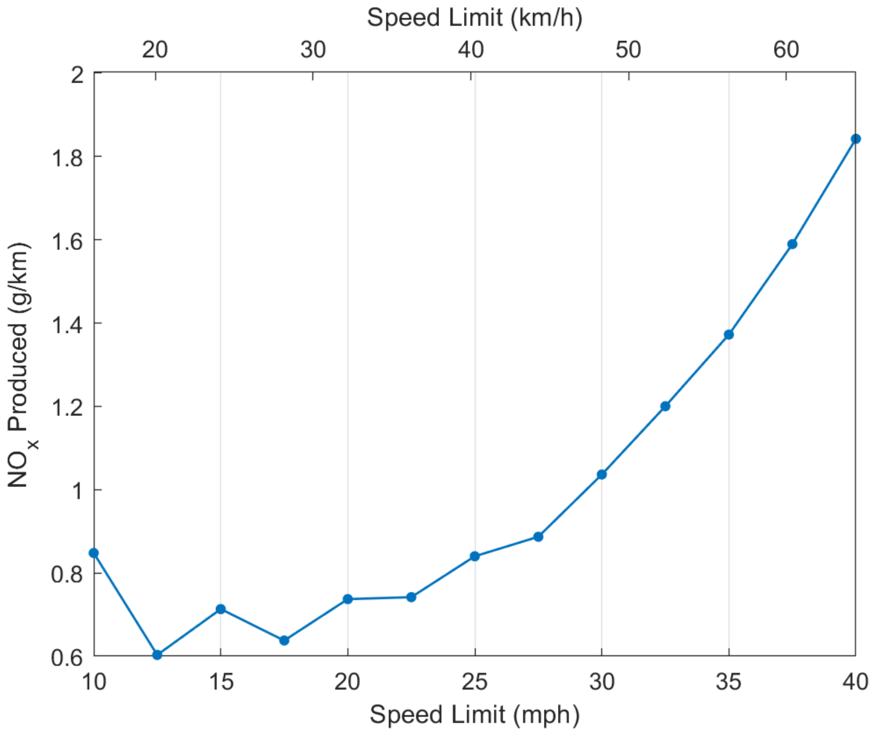

Figure 17. NOx emissions per kilometre travelled for a simulated 2016 Ford Focus TDCi.

Impact of Driving Style

To model the impact of different driving style, the simulations were repeated for vehicles at different accelerations and using different thresholds at which the vehicle will shifts up a gear when accelerating. Three different accelerations and three different up-shift thresholds were paired together to create conservative, balanced and aggressive driving styles. These styles are summarised in Table 9 and Table 10 for the simulated petrol and diesel vehicles respectively. The petrol vehicle shift thresholds are slightly higher than those of the diesel to reflect how these vehicles are driven in practice.

Table 9. Engine speed (RPM) at which the 2016 Ford Focus TDCi (Diesel) shifts up a gear whilst accelerating for different modelled driving styles.

	Engine Speed Shift Up Threshold	Acceleration
Conservative	2000 RPM	0.8 m/s^2
Balanced	2500 RPM	1.2 m/s^2
Aggressive	3000 RPM	1.6 m/s^2

Table 10. Engine speed (RPM) at which the 2016 Ford Focus EcoBoost (Petrol) shifts up a gear whilst accelerating for different modelled driving styles.

	Engine Speed Shift Up Threshold	Acceleration
Conservative	2250 RPM	0.8 m/s^2
Balanced	2750 RPM	1.2 m/s^2
Aggressive	3250 RPM	1.6 m/s^2

Figure 18 shows the difference in the average speed attained by the vehicles for different speed limits and under different driving styles. Below speed limits of 30mph (48.3km/h), there is little increase in average speed attained for each driving style. Using the balanced rather than conservative driving style results in a 1.9% increase in average speed at a speed limit of 20mph (32.2km/h), whilst using the aggressive driving style results in a 2.5% increase. There is little difference between the balanced and aggressive driving styles, but a noticeable difference to the conservative driving style at the higher speed limits. Using the balanced rather than conservative driving style results in a 5.2% increase in average speed at a speed limit of 30mph, whilst using the aggressive driving style results in a 7.7% increase.

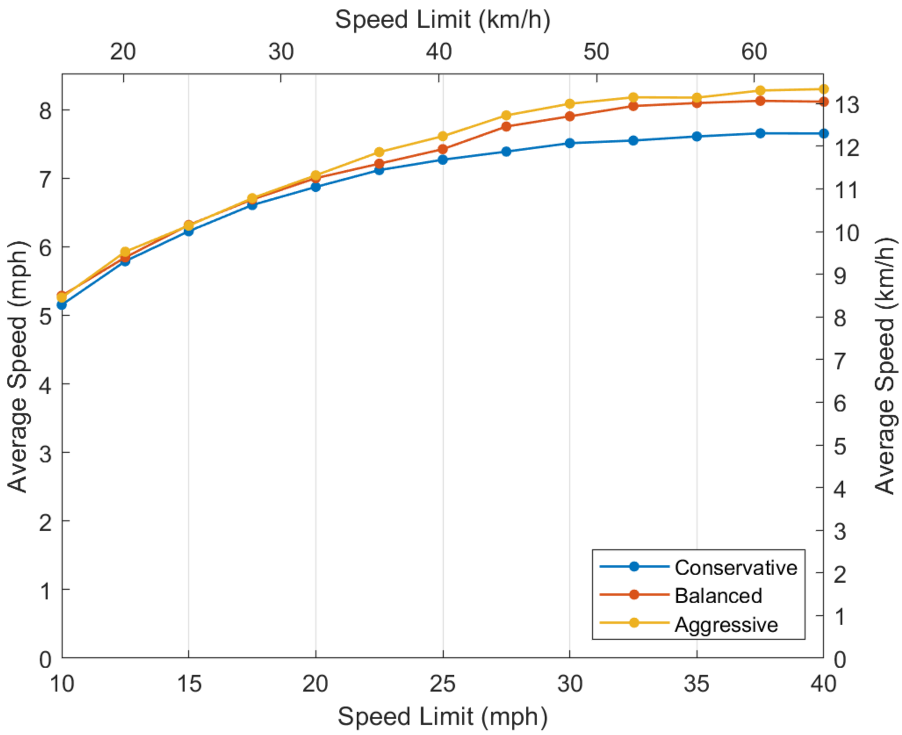

Figure 18. Average speed over the simulated journey for a 2016 Ford Focus EcoBoost at different driving style.

This difference is not just because driving using a higher acceleration gives the vehicles a greater chance of passing traffic lights before they turn red, but also because for a 160m spacing of traffic lights, a vehicle accelerating at $0.8m/s^2$ would only achieve a maximum speed of 35.8mph (57.6km/h). This means that these vehicles would not reach the speed limit before slowing down for the upcoming traffic lights, thus lowering their average speed. For accelerations of 1.2m/s^2 and 1.6m/s^2, the vehicles would be able to reach the maximum speed limit of 40mph (64.4km/h) between each set of lights, assuming they had space to the vehicle in front. Vehicles accelerating at 1.2m/s^2 would reach 40mph after 132.9m and vehicles accelerating at 1.6m/s^2 would reach 40mph after 99.7m.

The difference in energy required and CO_2 emissions when driving at different driving styles is shown in Figure 19. Both the difference in acceleration and up-shift thresholds have an impact of the emissions. An increase in acceleration creates and increase in torque demand, which changes the brake specific fuel consumption by moving the point of interest further up the BSFC map. An increase in up-shift threshold also increases the brake specific fuel consumption by moving the point of interest further to the right of the BSFC map. This can be seen in Figure 20 by the lines tracing the brake specific fuel consumption at each gear when accelerating from 0mph to 60mph (96.6km/h) using the conservative and aggressive driving styles. Once the vehicle has reached the target speed, it will stop accelerating and the required torque will drop significantly.

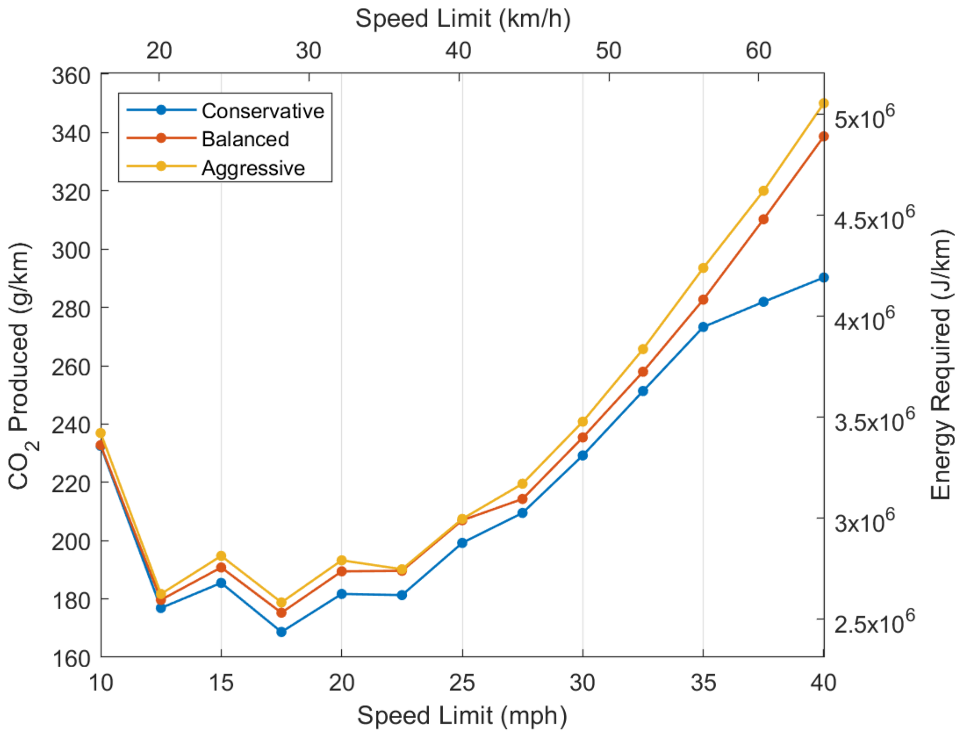

Figure 19. CO2 emissions and energy required per kilometre travelled for a simulated 2016 Ford Focus EcoBoost at different driving style.

Below 35mph (56.3km/h), all three driving styles result in similar emissions, with the conservative driving style only being slightly more efficient. Using the conservative driving style requires 2.6% less energy than the balanced driving style at a speed limit of 30mph (48.3km/h), whilst it requires 4.8% less energy than the aggressive driving style. There is a considerably larger improvement from lowering the speed limit from 30mph (48.3km/h) to 20mph, than there is from driving conservatively rather than aggressively. Using the conservative driving style, 26.1% more energy is required to drive at to a speed limit of 30mph rather than 20mph, for only a 9.3% increase in average speed. Like the difference in average speed plot in Figure 18, the largest difference is between the conservative driving style and the other two driving styles at the higher speed limits. Again, this is because vehicles accelerating at 0.8m/s^2 can only reach a maximum speed of 35.8mph (57.6km/h) over the traffic light spacing of 160m.

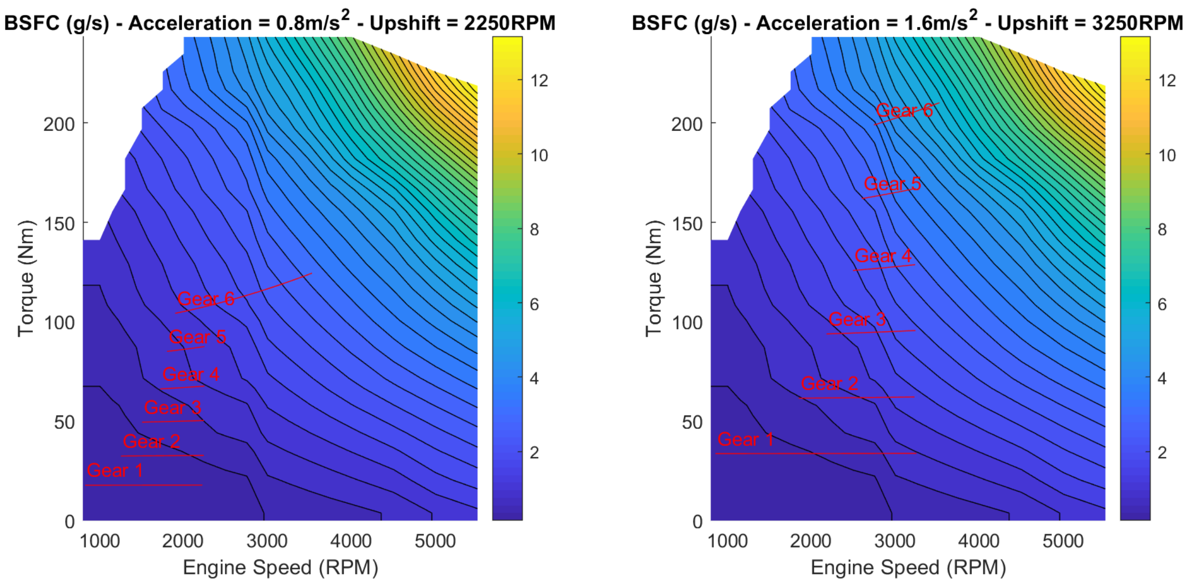

Figure 20. Brake specific fuel consumption for conservative and aggressive driving styles for a simulated 2016 Ford Focus EcoBoost whilst accelerating from 0mph to 60mph (96.6km/h).

Similar relationships can be seen in the NO_x emissions shown in Figure 21. Using the conservative driving style at a speed limit of 20mph (32.2km/h) results in 7.7% fewer NO_x emissions relative to the balanced driving style and 11.5% fewer NO_x emissions relative to the aggressive driving style. However, driving to a speed limit of 20mph rather than 30mph (48.3km/h) results in 51.0% fewer NO_x emissions, showing again that a reduction in speed limit has a significantly greater impact on emissions than a change in driving style. Again, for such a significant reduction in emissions, a speed limit of 30mph only results in a 9.3% increase in average speed.

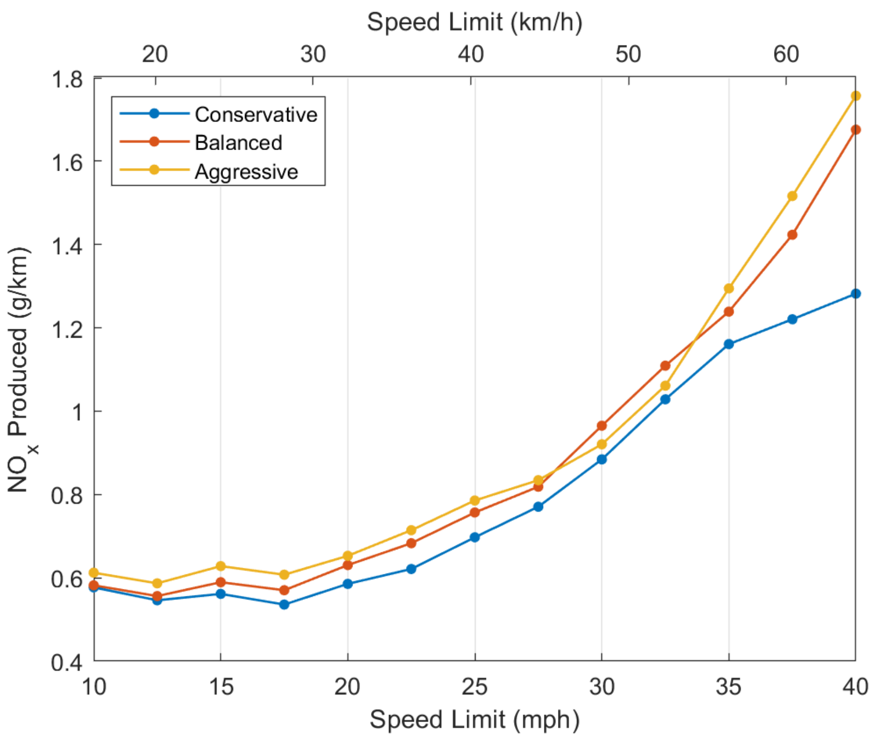

Figure 21. NOx emissions per kilometre travelled for a simulated 2016 Ford Focus TDCi at different driving style.

Impact of Vehicle Size

To investigate the impact of vehicle size on fuel efficiency and emissions, a large SUV was modelled and compared to the previously modelled Ford Focus. A 2016 Mazda CX-9 was chosen. These vehicles both have petrol engines, but the Mazda CX-9 uses a 2.5l engine rather than the 1.6l engine used by the Ford Focus. The Mazda CX-9 has a mass of 1951kg, which is 50.8% more than the mass of the Ford Focus which is 1294kg. The same simulations were carried out using this vehicle, with an acceleration of 1.2m/s^2 and a threshold for shifting up a gear whilst accelerating of 2250RPM.

The comparison of fuel efficiencies can be seen in Figure 22. For the same journey, the Mazda CX-9 is considerably more inefficient than the Ford Focus. The Mazda CX-9 requires 64.8% more energy to complete the same journey at a speed limit of 30mph (48.3km/h), resulting in a fuel efficiency of 17.8mpg in comparison to the Ford Focus's fuel efficiency of 29.3mpg. At 20mph (32.2km/h) the Mazda CX-9 requires 57.3% more energy, resulting in a fuel efficiency of 22.7mpg in comparison to the Ford Focus's fuel efficiency of 35.8mpg. The increase in energy requirements is primarily due to the increase in mass that the engine is required to accelerate up to the speed limit, but also somewhat due to the poorer aerodynamic characteristics of larger vehicles.

This investigation does not account for different vehicles lengths and its impact on traffic density in the simulations, but the greater length of the Mazda CX-9 (5.065m) relative to the Ford Focus (4.358m) would also have the effect of slowing traffic further as each SUV has a larger footprint on the road. Driving smaller cars would allow more vehicles to fit on a stretch of road, allowing for a better flow of traffic.

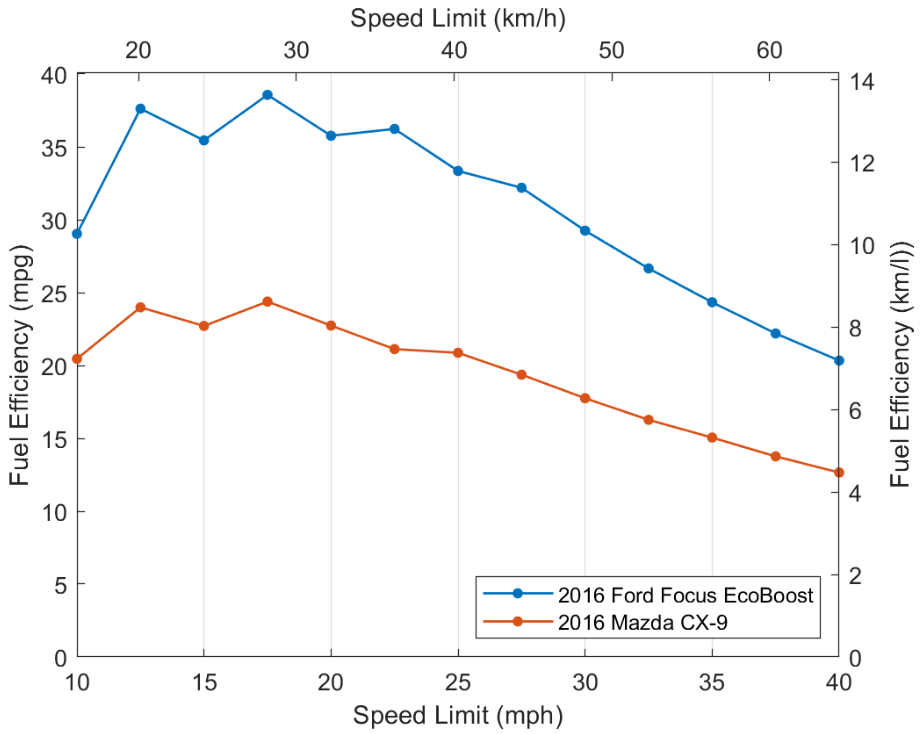

Figure 22. Fuel efficiency under urban traffic conditions for a simulated 2016 Ford Focus EcoBoost and 2016 Mazda CX-9.

Diesel vs Petrol CO_2 emissions

Two similarly sized SUV vehicles were modelled to investigate the difference between petrol and diesel engines under urban traffic conditions. A 2015 BMW X5 was modelled which used a 3.0l BMW

N57 diesel engine. This vehicle is of a similar size and mass to the previously modelled petrol engine Mazda CX-9.

The difference in energy required at different speed limits for the two vehicles can be seen in Figure 23. The diesel engine BMW X5 requires more energy than the petrol engine Mazda CX-9. At a speed limit of 30mph (48.3km/h) the BMW X5 requires 13.1% more energy than the Mazda CX-9. Similar differences in energy required are seen at all speed limits above 25mph (40.2km/h). At 20mph (32.2km/h) the BMW X5 requires 5.1% more energy.

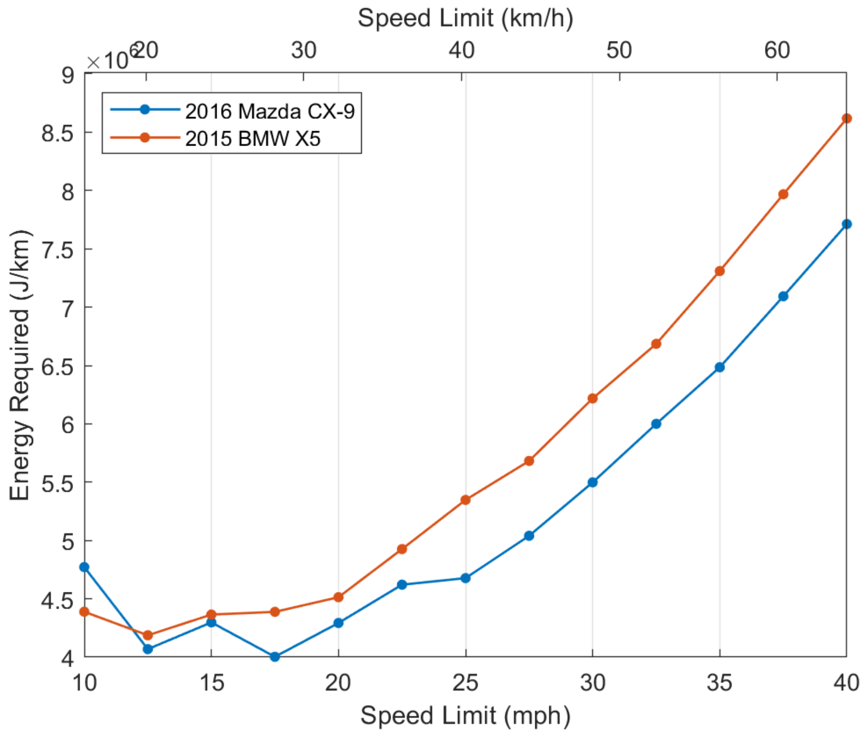

Figure 23. Energy required for a simulated 2016 Mazda CX-9 (petrol) and 2015 BMW X5 (diesel).

The density of petrol and diesel vary somewhat, particularly with temperature, but diesel has a density of approximately 0.85kg/l, whereas petrol is less dense at approximately 0.75kg/l. Both fuels contain similar amounts of energy density per unit mass, but diesel contains greater energy per unit volume. This results in similar fuel efficiencies for the two vehicles when measured in terms of mpg. This can be seen in Figure 24. Although the diesel engine requires more energy, the fuel efficiency is very similar for these two vehicles, particularly at speed limits greater than 25mph (40.2km/h). This is difference that customers see in practice as fuel is purchased in units of volume and not mass.

The comparison of CO_2 emissions between the two vehicles can be seen in Figure 25. Although the diesel engine requires more energy, it can be seen that the petrol engine Mazda CX-9 produces more CO_2 emissions than the diesel engine BMW X5. At a speed limit of 30mph (48.3km/h) the Mazda CX-9 produces 24.3% more CO_2 emissions than the BMW X5. Similar differences in emissions are seen at all speed limits. At 20mph (32.2km/h) the increase in emissions is 33.7%. NO_x emissions maps were not available for these engines so NO_x emissions could not be modelled. However, it can be assumed that the NO_x emissions of the diesel engine vehicle would be considerably higher, particularly when driving under urban traffic conditions.

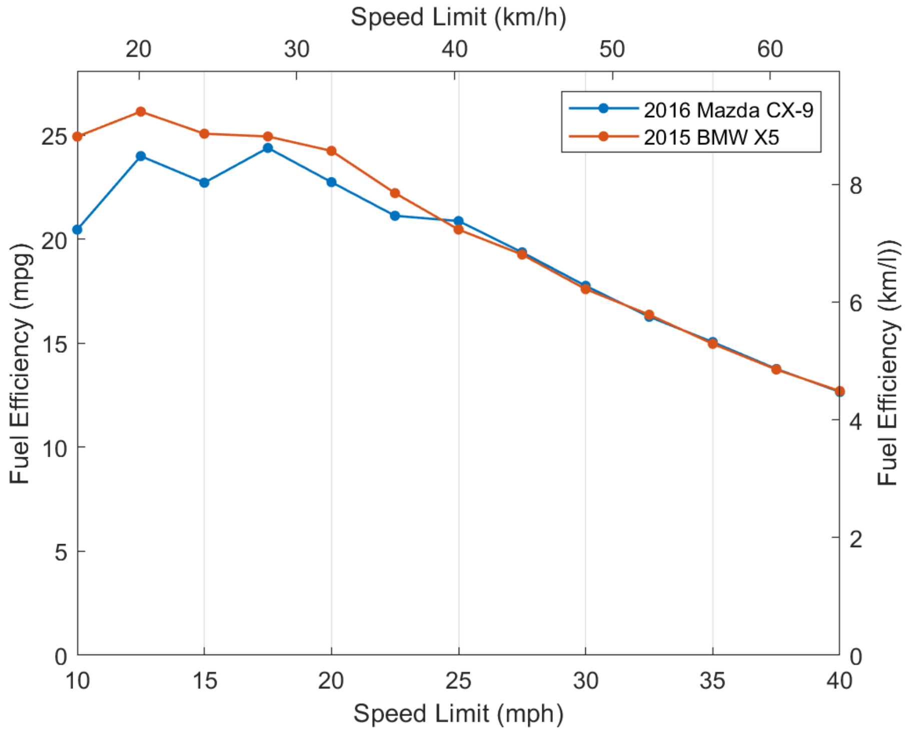

Figure 24. Fuel efficiency for a simulated 2016 Mazda CX-9 (petrol) and 2015 BMW X5 (diesel).

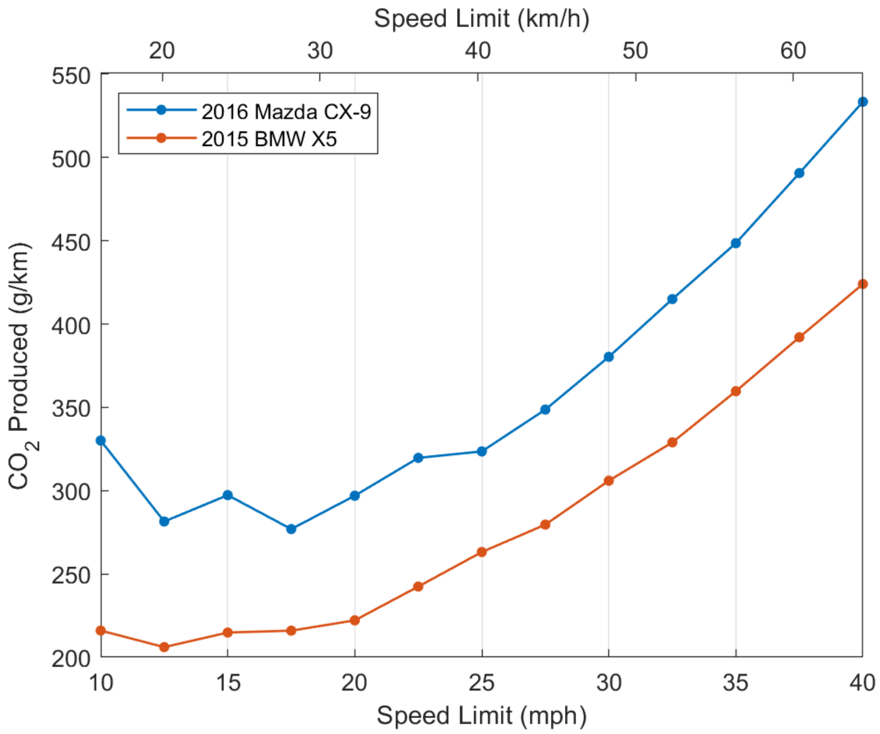

Figure 25. CO2 emissions for a simulated 2016 Mazda CX-9 (petrol) and 2015 BMW X5 (diesel).

Conclusions

The model developed as part of this investigation was shown to be representative of London traffic. The model simulated average speed of travel under urban traffic conditions at a speed limit of 25mph (40.2km/h) was found to be 7.43mph (11.96km/h), which is very close to the TfL published average speed of 7.4mph in London [5]. The model was also validated against experimentally measured CO_2 and NO_x emissions for a Ford Focus TDCi over 185km of driving. The model predicted emissions agreed well with the experimental data.

It was found that the energy required to accelerate vehicles to the speed limit was the largest contributor to fuel consumption in urban traffic conditions. Vehicles are often more efficient at higher speeds, but this does not account for the energy required to reach these speeds. For the modelled Ford Focus EcoBoost a cruising speed of 30mph (48.3km/h), accounting for the acceleration phase, is only more efficient than a cruising speed of 20mph (32.2km/h) if the vehicle can drive for 0.48km without stopping, which is unlikely under urban driving conditions. At 40mph (64.4km/h), this distance increases to 1.61km. The modelled Mazda CX-9 is more efficient after 1.23km and the modelled BMW X5 is never more efficient at 30mph rather than 20mph.

Under the modelled urban traffic conditions, it was found that there is little improvement in average speed of travel for speed limits above 25mph. The increase in emissions at higher speed limits was greater than the increase in average speed. For the Ford Focus EcoBoost it was found that a speed limit of 30mph results in 22.3% more CO_2 emissions and 40.6% more NO_x emissions than travelling at a speed limit of 20mph, for only a 12.9% increase in average speed of travel. Fuel efficiency follows the same trend, resulting in an efficiency of 29.3mpg at 30mph, and 35.8mpg at 20mph.

Different driving styles were modelled, and it was found that an aggressive driving style resulted in a 4.8% increase in CO_2 emissions and energy required relative to a conservative driving style at a speed limit of 30mph. However, this is considerably less than the improvements seen above from reducing the speed limit from 30mph to 20mph.

The modelled Mazda CX-9 SUV showed that the CO_2 emissions, energy required and fuel efficiency all scale with the size of the vehicle. This SUV required 64.8% more energy than the Ford Focus hatchback to travel at a speed limit of 30mph under the modelled urban traffic conditions. The increased size and associated increase in emissions makes such large vehicles unsuited for urban travel.

The modelled diesel engine BMW X5 SUV performed similarly to the petrol engine Mazda CX-9. These vehicles had similar fuel efficiencies, and although the diesel vehicle has fewer CO_2 emissions, the NO_x emissions are likely considerably larger, although this was not modelled here. Both vehicles are unsuited to urban travel when compared with the Ford Focus.

References

[1] S. C. Davis, S. W. Diegel and R. G. Boundy, Transportation Energy Data Book (31st ed.), Knoxville: Oak Ridge National Laboratory, 2012.

[2] A. Arbor, “2013 Ford 1.6L EcoBoost Engine Tier 2 Fuel - ALPHA Map Package,” 2018. [Online]. Available: https://www.epa.gov/vehicle-and-fuel-emissions-testing/combining-data-complete-engine-alpha-maps.

[3] A. Arbor, “2016 Mazda 2.5L Turbo Skyactiv-G Engine Tier 2 Fuel - ALPHA Map Package,” 2018. [Online]. Available: https://www.epa.gov/vehicle-and-fuel-emissions-testing/combining-data-complete-engine-alpha-maps.

[4] A. Arbor, “2015 BMW 3.0L N57 Engine Diesel Fuel - ALPHA Map Package,” 2018. [Online]. Available: https://www.epa.gov/vehicle-and-fuel-emissions-testing/combining-data-complete-engine-alpha-maps.

[5] Transport for London, “TLRN Performance Report, Quarter 1 2017/2018,” 2018. [Online].

Available: https://content.tfl.gov.uk/tlrn-performance-report-q1-2017-18.pdf.

[6] UK Department for Transport, “The Highway Code,” 2015. [Online]. Available: https://www.gov.uk/guidance/the-highway-code.

[7] automobile-catalog, “2016 Ford Focus 1.5 EcoBoost (150) (man. 6) (Business, Titanium) (model for Europe) car specifications & performance data review,” 2022. [Online]. Available: https://www.automobile-catalog.com/car/2016/2082470/ford_focus_1_5_ecoboost_150.html.

[8] automobile-catalog, “2016 Ford Focus 1.5 TDCi (120) (man. 6) (Trend, Business, Titanium) (model for Europe) car specifications & performance data review,” 2022. [Online]. Available: https://www.automobile-catalog.com/car/2016/2082560/ford_focus_1_5_tdci_120.html.

[9] automobile-catalog, “2016 Mazda CX-9 Grand Touring AWD (aut. 6) (model since April 2016 for North America) car specifications & performance data review,” 2022. [Online]. Available: https://www.automobile-catalog.com/car/2016/2407130/mazda_cx-9_grand_touring_awd.html.

[10] automobile-catalog, “2015 BMW X5 xDrive30d (aut. 8) (model for Europe) car specifications & performance data review,” 2022. [Online]. Available: https://www.automobile-catalog.com/car/2015/1902395/bmw_x5_xdrive30d.html.