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

An innovative model-based approach was used to investigate the effect of maximum vehicle speed, driving style and vehicle type on average journey speeds, CO_2 and NO_x emissions and fuel efficiency in typical urban traffic. A traffic simulator model was created and calibrated to be representative of London roads, and the predictions were validated against experimental data from real world driving.

It was found that higher speed limits, resulting in higher peak vehicle speeds, 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 35.9% 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 showed the average journey time was 7% higher at 20mph than at 30mph. A diesel Ford Focus TDCi travelling at a speed limit of 30mph (48.3km/h) resulted in 78.8% more NO_x emissions than travelling at a speed limit of 20mph. Higher speed limits, resulting in higher peak speeds between acceleration and deceleration events, were found to have a significantly greater impact of emissions and fuel efficiency than a change in driving styles. An aggressive driving style resulted in a 8.5% increase in fuel consumption at 30mph versus a conservative one. Vehicle size was also found to impact the emissions and fuel efficiency, with the difference in fuel efficiency between the different peak speeds 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 norm, 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 supplied to us by Emission Analytics. 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. The results were validated experimentally by the authors driving a simple test route to different speed limits and using the built-in average fuel consumption measurements in the vehicle's own trip computer to measure the fuel efficiency.

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). It is thought that 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 was originally documented 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.

The Oak Ridge data is also based on constant speed driving, which means the effect of acceleration up to the different speeds is ignored. In urban driving with frequent accelerations and decelerations, this effect is significant, and makes a big difference to the relationship between speed and fuel efficiency/emissions.

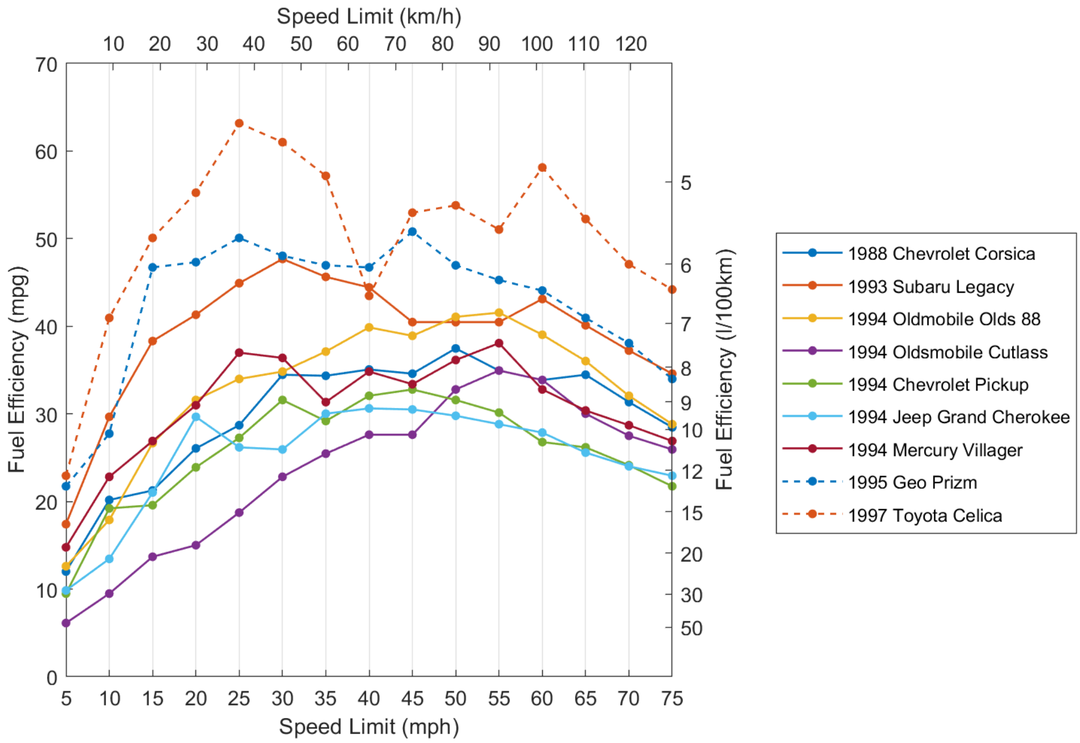

Figure 1. Often quoted, although outdated and incorrect data showing the optimum fuel efficiency of vehicles is around 55mph [1].

The validated model we developed was 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.

Petrol engines often perform less inefficiently at lower power output (commensurate with the engine doing less work at low speeds), because the partially opened throttle acts as a flow restriction on the air intake during the induction stroke, which is a waste of energy. However, the vehicle they are propelling requires more energy initially to accelerate to reach higher speeds, and more energy to overcome air resistance and rolling resistance at higher speeds. The two effects act in different directions at different speeds, so the relationship between speed and fuel efficiency is not a simple straight line, as can be seen in the figure above. The relationship also depends upon the acceleration loads as well as the peak speed. To investigate the combined effects, the model was also used to measure the travel distance without stopping and starting above which higher speed limits become more efficient than lower speed limits for different vehicles.

Finally, an adapted version of the model was used to simulate the behaviour of the different vehicles driving the Worldwide Harmonised Light Vehicle Test Procedure (WLTP) velocity profile, the global standard test procedure used to measure the emissions and fuel efficiencies of all new vehicles.

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 dense cities or urban roads with reasonably frequent junctions.

The traffic was modelled as a queue of identical vehicles that crossed a series of traffic lights, which each represent 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 major London roads (the A23, A2, A315 and 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 swept to find the duty cycle that best matched the quoted traffic speeds. This was found to be 70%, meaning that the lights were on red for 70% of the time, and green for 30%. Consequently the vehicles in the model stop and start on average every 230m. This compares well to empirical data gathered from a GPS tracker used in a vehicle to log the speed at 2 seconds intervals on a drive through London.

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 in front.

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.

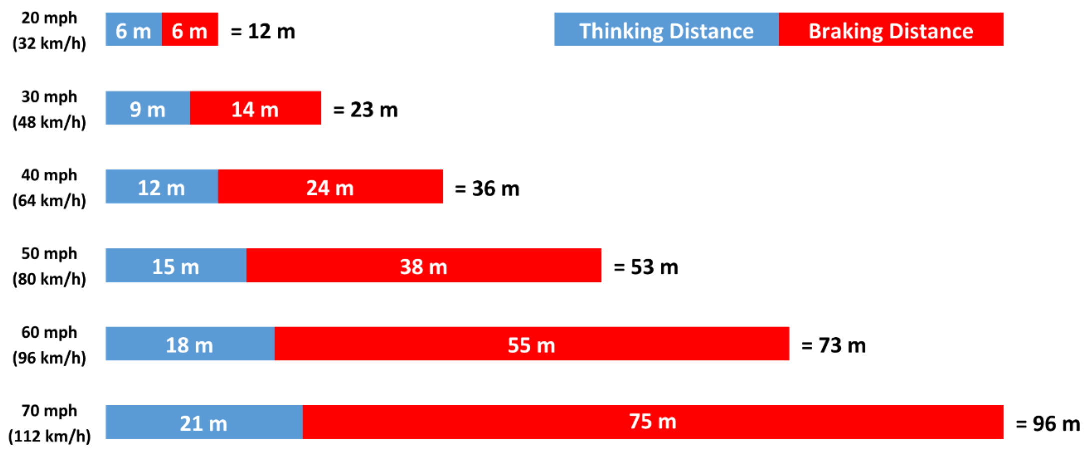

Figure 2. Stopping distance guide for a vehicle according to rule 126 of the UK Highway Code [6].

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):

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

The traffic simulation model was written in Matlab. The simulator was animated to scale, which permitted a subjective validation that the vehicle behaviour 'looked representative of real-world traffic behaviour.

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):

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

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.

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

For a vehicle that is accelerating rather than travelling at a constant velocity, the force required to accelerate, F_a (N), must also be accounted for, as shown in Eq. 8.

$$F = F_d + F_r + F_a \quad \text{Eq. 8}$$

The force required to accelerate is calculated using Eq. 9, where m is the vehicle mass including a driver (kg) and m_e (kg) is the additional equivalent non-rotating mass of the rotating components of the drivetrain.

$$F_a = (m + m_I) a_n \quad \text{Eq. 9}$$

The equivalent non-rotating mass is a function of a component static mass and its rotational inertia. For simplicity, the additional equivalent non-rotating mass of the wheel assembly (wheel rim, tyre, brakes) is assumed to be equivalent to 4% of the vehicle mass, and as such scales with the size of the vehicle as would be expected. The additional equivalent non-rotating mass of the flywheel and CV axles are calculated separately. Additionally, the additional equivalent non-rotating mass of the driveshaft and rear-axle are calculated for rear-wheel drive and 4-wheel drive vehicles.

For any rotating component, the kinetic energy of a moving object is equivalent to its rotational energy, such that Eq. 10 applies, where I (kg m^2) is the rotational moment of inertia of the component and ω is the angular velocity (rad/s).

$$\frac{1}{2} m_e v^2 = \frac{1}{2} I \omega^2 \quad \text{Eq. 10}$$

All the modelled rotating components can be model as rotating cylinders or discs, such that their rotational moment of inertia is given by Eq. 11, where m (kg) is the static mass of the component and r (m) the outer radius of the cylinder or disc.

$$I = \frac{1}{2} m r^2 \quad \text{Eq. 11}$$

The CV axles and rear axle rotate at the same angular velocity as the wheels of the vehicle, such that rearranging Eq.10 and Eq. 11 allows the equivalent non-rotating mass of these component to be calculated from Eq. 12.

$$m_e = \frac{1}{2} m_{component} \left(\frac{r_{component}}{r_{wheel}} \right)^2 \qquad \text{Eq. 12}$$

In rear-wheel drive and 4-wheel drive vehicles the driveshaft will rotate at the final drive ratio relative to the wheels, such that its equivalent non-rotating mass can be calculated from Eq. 13.

$$m_e = \frac{1}{2} m_{component} \left(F_d \cdot \frac{r_{component}}{r_{wheel}} \right)^2 \qquad \text{Eq. 13}$$

The flywheel is larger in mass and greater in diameter that the previously mentioned drivetrain components. It also rotates at a much higher angular velocity. Whereas the other components rotate at some fixed ratio to the wheels, the ratio at which the flywheel rotates relative to the wheels varies depending on the current gear. As such, a more in-depth approach is required.

A different equivalent non-rotating mass of the flywheel is calculated for each of the vehicle's selectable gears. For each gear, this is the average equivalent non-rotating mass that the flywheel would exhibit over the range of engine speeds in which that gear is used. Each gear is assumed to be used up until some defined engine speed at which the driver shifts up to the next gear, such there exists a start and end engine speed, ω_{start} and ω_{end} (rad/s), and a start and end vehicle velocity, v_{start} and v_{end} (m/s), over which this gear was used. For all but the final gear, ω_{end} (rad/s) is this defined engine speed at which the driver shifts up to the next gear. For the final gear, ω_{end} is the highest engine speed that the driver will reach in typical use and is assumed to be 3500RPM in this model. From these engine speeds, the corresponding vehicle velocity when the driver shifts the vehicle up a gear, v_{end} (m/s), can be calculated using Eq. 14, where GR is the current gear ratio, FD is the final drive ratio and r is the radius of the wheel.

$$v = \frac{\omega \cdot r}{GR \cdot FD} \qquad \text{Eq. 14}$$

In first gear the starting velocity, v_{start}, is 0m/s. For each subsequent gear, the starting velocity is the end velocity of the previous gear. From these starting velocities, the starting angular velocity, ω_{start} (rad/s), can be calculated by rearranging Eq. 14. In first gear, ω_{start} (rad/s) is the engine speed as controlled by the driver at which the vehicle launches, and in this model was assumed to be 1500RPM.

Knowing these velocities, the difference in flywheel energy between the start and end of any gears practical range of use can be expressed as the sum of the kinetic energy increase and the rotational energy increase, as shown in Eq. 15.

$$\Delta E = \frac{1}{2} m_{flywheel} \left(v_{end}^2 - v_{start}^2 \right) + \frac{1}{2} I (\omega_{end}^2 - \omega_{start}^2) \qquad \text{Eq. 15}$$

In practice, the total energy to reach the current flywheel state at engine speed ω, vehicle velocity v, and in gear n, is the sum of the energies of each of the gears up to gear n and the energy to go from v_{start} to v in gear n. For simplicity, the energy required to reach a specific speed in gear n is not calculated. Instead, the energy required is approximated as the sum of the energies up to and including the full range of gear n, as shown in Eq. 16.

$$E_n = \Delta E_1 + \sum_{i=2}^{n} \Delta E_i \qquad \text{Eq. 16}$$

As the vehicles shifts up by a gear, the engine speed will decrease. This means that the angular velocity of flywheel must also decrease to match, and in doing so reduce its rotational energy. Much of the energy is dissipated as heats, but some of this energy it transferred back into the drivetrain. Eq. 16 does not account for this energy recovery from the flywheel. The energy lost by the flywheel in a gear shift is calculated from Eq. 17.

$$E_{lost} = \frac{1}{2} I\left(\omega_{end\ gear\ n-1}^2 - \omega_{start\ gear\ n}^2\right) \qquad \text{Eq. 17}$$

If some proportion, η, of this lost energy is recovered, then for each upwards gear shift Eq. 16 becomes Eq. 18.

$$E_n = \Delta E_1 + \sum_{i=2}^{n} (\Delta E_i - \eta E_{i\ lost}) \qquad \text{Eq. 18}$$

With the energy required to reach each gear known, the equivalent non-rotating mass for the flywheel in each gear can be calculated by rearranging the flywheel's kinetic energy equation into Eq. 19. This can then be used to calculate the force required to accelerate the vehicle using Eq. 9.

$$m_e = \frac{2E}{v_{end}^2} \qquad \text{Eq. 19}$$

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. 20, 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):

$$\omega_{RPM} = v\, GR\, FD \left(\frac{60}{2\pi r}\right) \qquad \text{Eq. 20}$$

Required Energy to Move

The power required, P (W), is calculated from Eq. 21. 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.

$$P = \frac{F v_n}{\eta} \qquad \text{Eq. 21}$$

From this power and the engine speed, the torque, T (Nm), required from the engine is calculated using Eq. 22.

$$T = P\left(\frac{60}{2\pi \omega_{RPM}}\right) \qquad \text{Eq. 22}$$

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.

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. 23 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).

$$E = f E_{pet} \Delta t \qquad \text{Eq. 23}$$

If the vehicle is idling rather than moving, the energy is calculated from Eq. 24, 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.

$$E = E_{pet} V_{eng} f_{idle} \Delta t \qquad \text{Eq. 24}$$

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

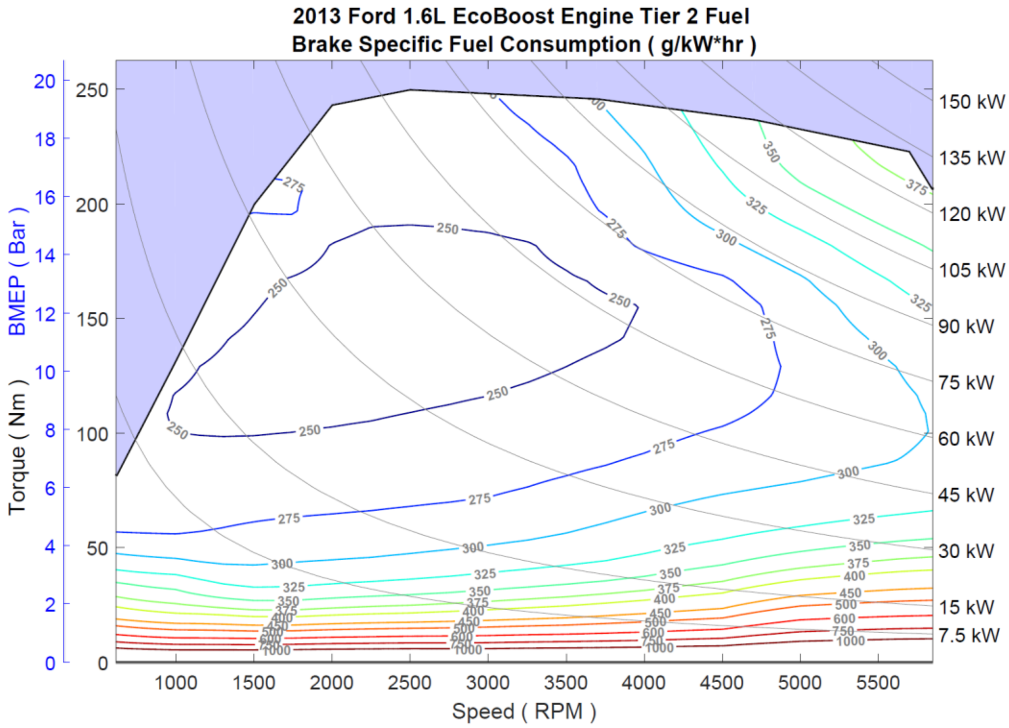

Figure 3. Brake Specific Fuel Consumption map for the 2013 Ford 1.6l EcoBoost Engine [2].

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. 25, where V_{pet} is the volume of petrol (l) and d_{total} is the total distance travelled by the vehicle over the journey (m):

$$CO_2 = \frac{2392 * \frac{E_{total}}{E_{pet}}}{d_{total}} \qquad \text{Eq. 25}$$

For diesel engine vehicles, 2640g of CO_2 is produced per litre of fuel burned, such that Eq. 26 is used instead.

$$CO_2 = \frac{2640 * \frac{E_{total}}{E_{diesel}}}{d_{total}} \qquad \text{Eq. 26}$$

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. The vehicle stayed below an engine speed of 2500 RPM throughout the tests, and typically stayed below an engine speed of 2250 RPM.

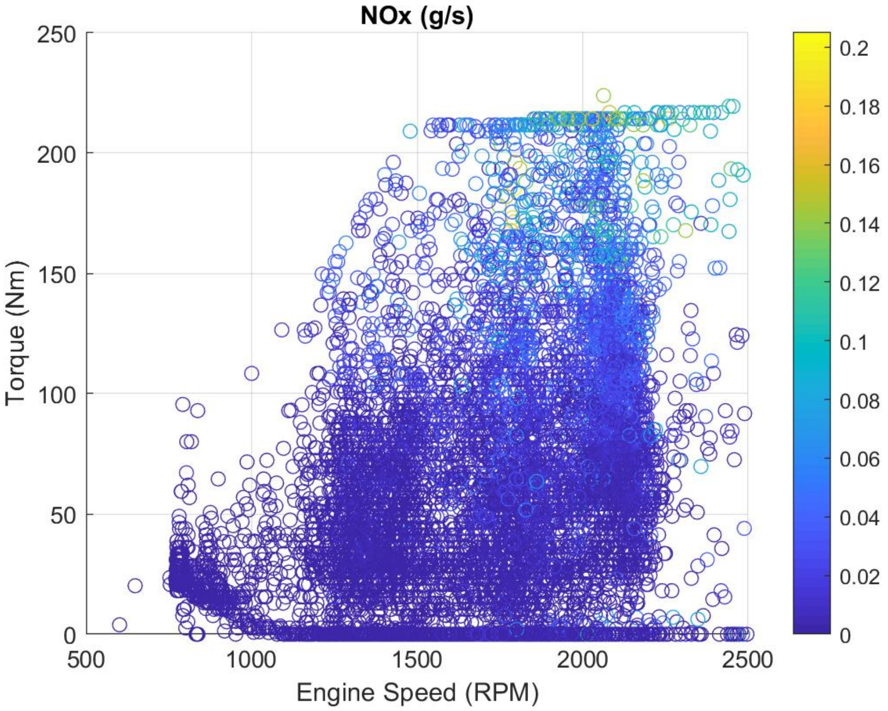

Figure 4. Real world NO_x emissions for a Ford Focus as a function of engine speed and supplied torque.

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.

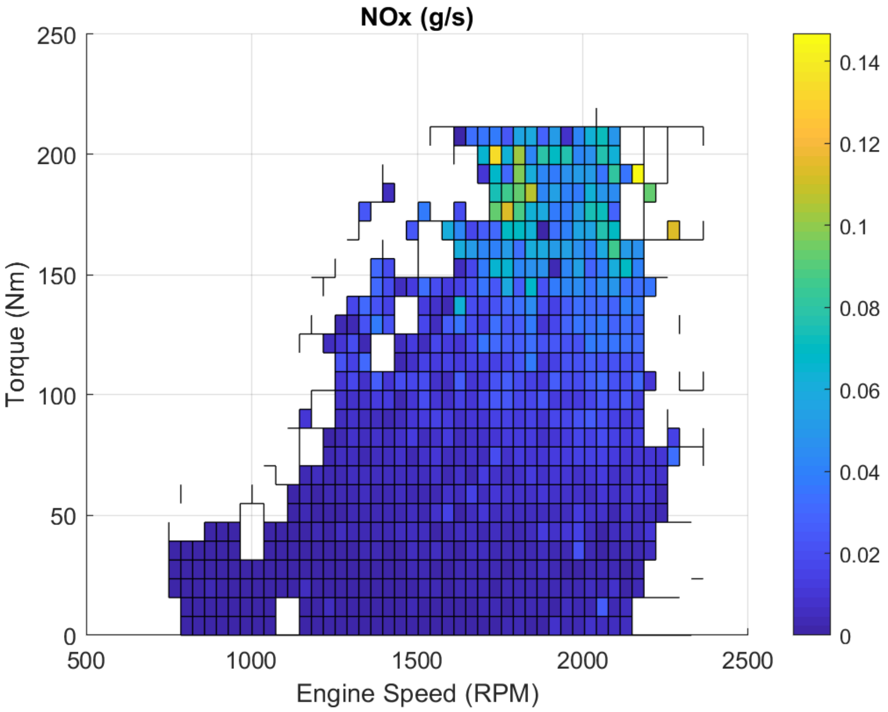

Figure 5. Mean NO_x value for each bin.

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.

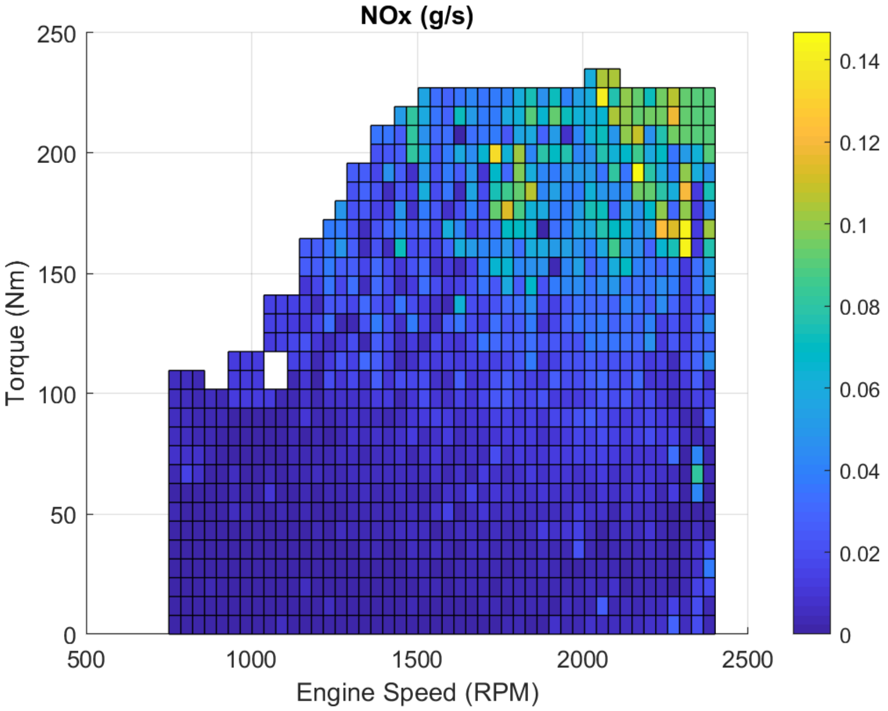

Figure 6. Mean NO_x map with missing data approximated using a moving average over a window size of 4 data points.

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. Note that NOx in grammes per second is more than 10 times higher when the torque is high whilst the vehicle is accelerating, than when the torque is lower when the vehicle is cruising.

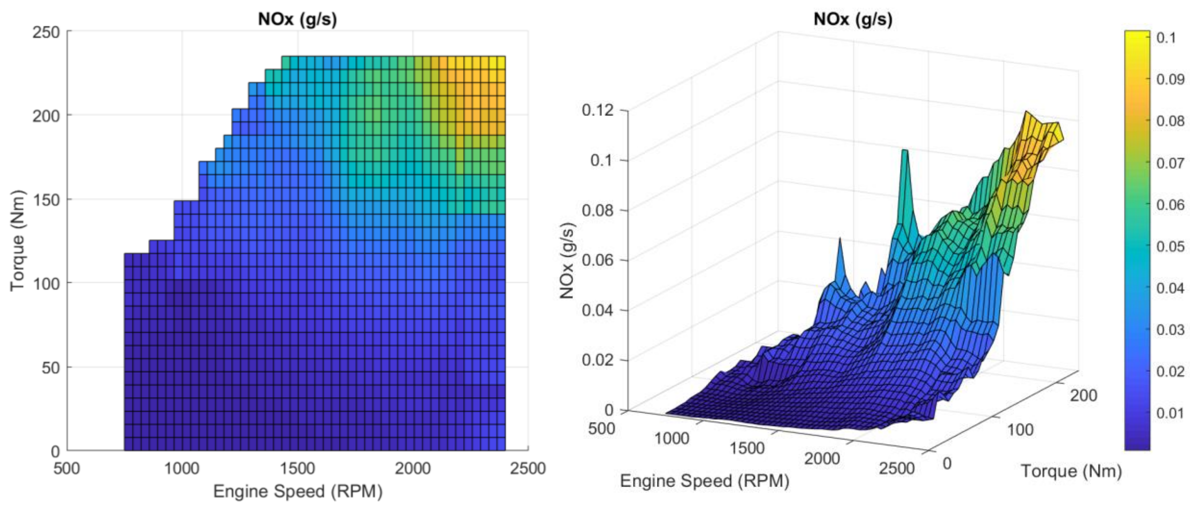

Figure 7. Final averaged NOx map.

Simulated WLTP

The model was also used to simulate the vehicle's fuel efficiency and emissions over the Worldwide Harmonised Light Vehicle Test Procedure (WLTP). This is the global standard test procedure used to measure the emissions and fuel efficiencies of all new vehicles. The WLTP consists of 4 sub-parts, each with a different top speed. The Low sub-part covers speeds up to 35.1mph (56.5 km/h). This covers a similar range of speeds as those seen in urban traffic conditions, and as such this is the sub-part that was simulated.

Unlike the traffic simulations, whereby the vehicle speed and position is calculated based on the traffic setup, these simulations use the vehicle WTLP speed profile as an input. The remainder of the model is as before, in that the fuel consumption and emissions are calculated from the energy required for the vehicle to achieve this speed for each time step.

To investigate the impact of speed limits on vehicle emissions, without the influence of the traffic model, adapted version of the WLTP were simulated. These adapted versions apply different maximum speed limits to the WLTP. When the speed is limited, the duration travelled (in seconds) is also extended, such that the distance covered between the start and end of the limited period is extended to match the distance covered when the base WLTP profile is used. This means that the adapted WLTP simulations all cover the same distances to allow for a fair comparison. The original and adapted WLTP profiles, limited to 30mph (48.3km/h), 20mph (32.2km/h) and 15mph (24.1km/h), can be seen in Figure 8.

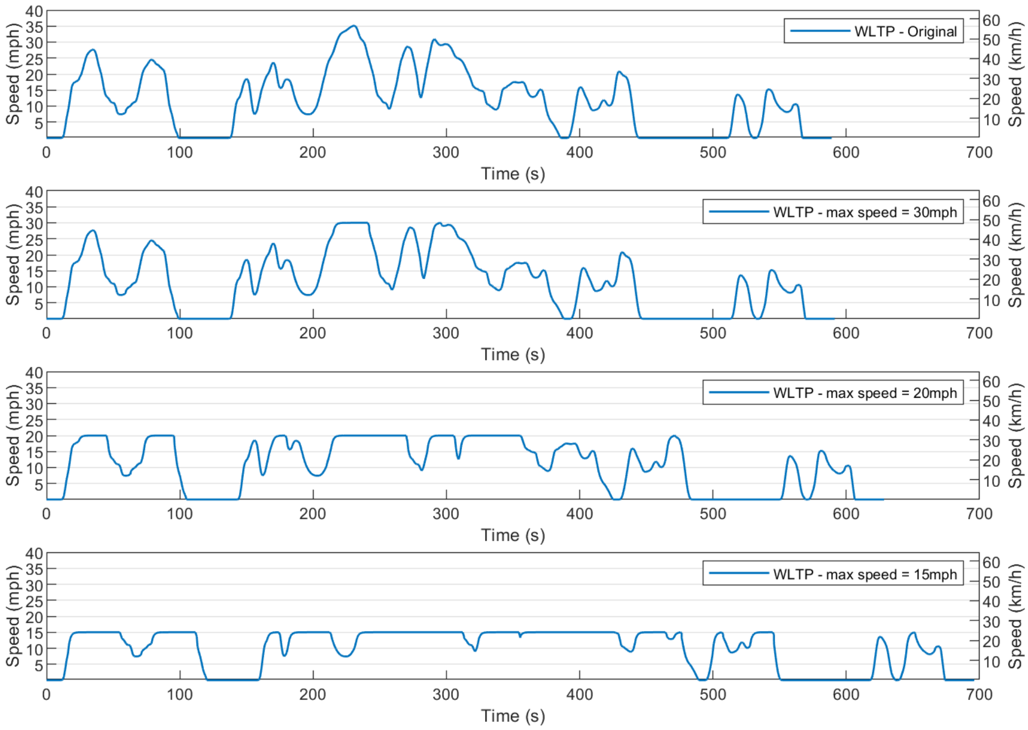

Figure 8. WLTP and adapted WLTP with max speed limits of 30mph (48.3km/h), 20mph (32.2km/h) and 15mph (24.1km/h).

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	0.316 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	0.316 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	0.369 m
Gear Ratios, GR	[3.487, 1.992, 1.449, 1, 0.707, 0.6]
Final Drive Ratio, FD	4.411

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

Vehicle mass, m	2070 kg
Coefficient of Drag, C_d	0.33
Frontal Area, A	2.84 m^2
Engine Capacity, V_{eng}	2.993 l
Tyre Pressure, p	2.14 bar
Wheel Radius, r	0.382 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

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.

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 9 and Figure 10 as a function of distance covered and time elapsed respectively. Both the real-world and model predicted NO_x emissions came to a total 126g over this 185km of driving. However, the profile of the NO_x emissions with both distance and time is noticeably different between the real-world and model simulate data. 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. In contrast, the model simulated emissions are much smoother. This is likely due to the NO_x emissions model being developed from a simplified and smoothed map of the real-world data, which over the distance modelled averages out to the same total NO_x emissions without the steps seen in the real-world data. The real-world emissions are initially higher than that of the model predictions before later converging. This could be due to the engine being more inefficient when starting cold, which is not accounted for in the model.

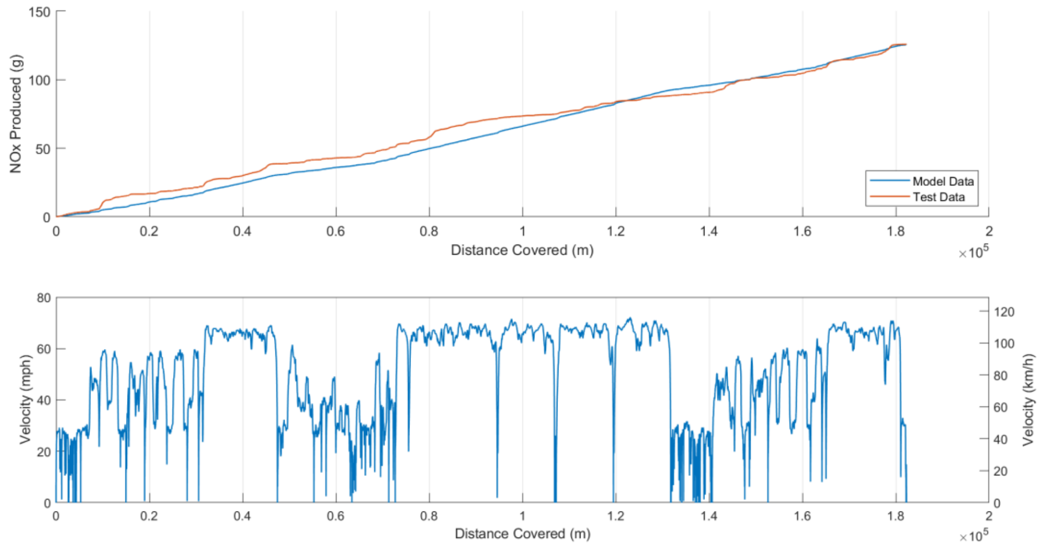

Figure 9. Real-world diesel NOx emissions vs model predicted diesel NOx emissions plotted as a function of distance covered.

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. This is an important consideration for traffic management. NOx emissions from individual idling vehicles are very low, it is the emissions when they subsequently accelerate that dominate. The emissions as a function of time show more variable rates, due to the varying speed of the vehicle over the journey.

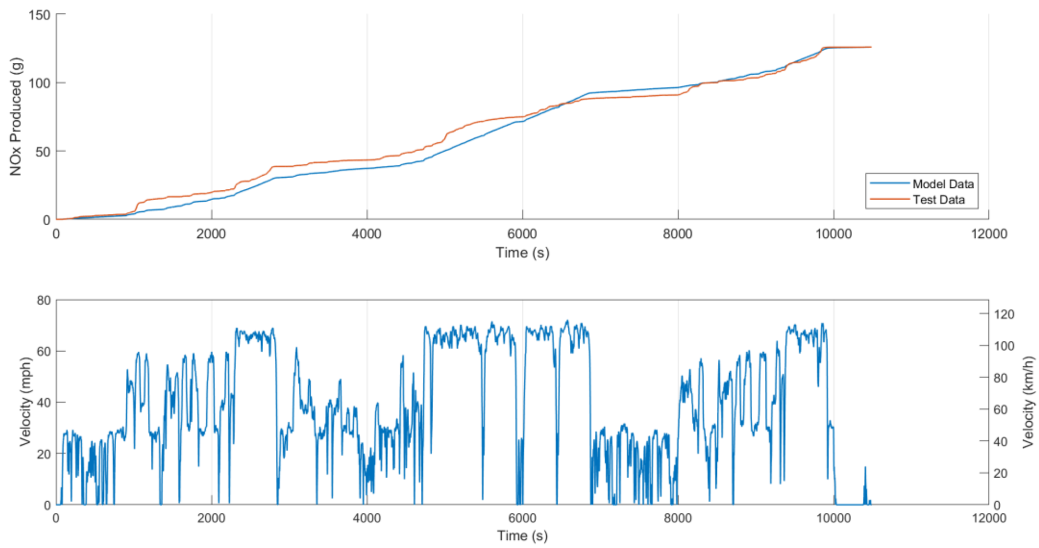

Figure 10. Real-world diesel NOx emissions vs model predicted diesel NOx emissions plotted as a function of elapsed time.

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 11 and Figure 12 as a function of distance covered and time elapsed respectively.

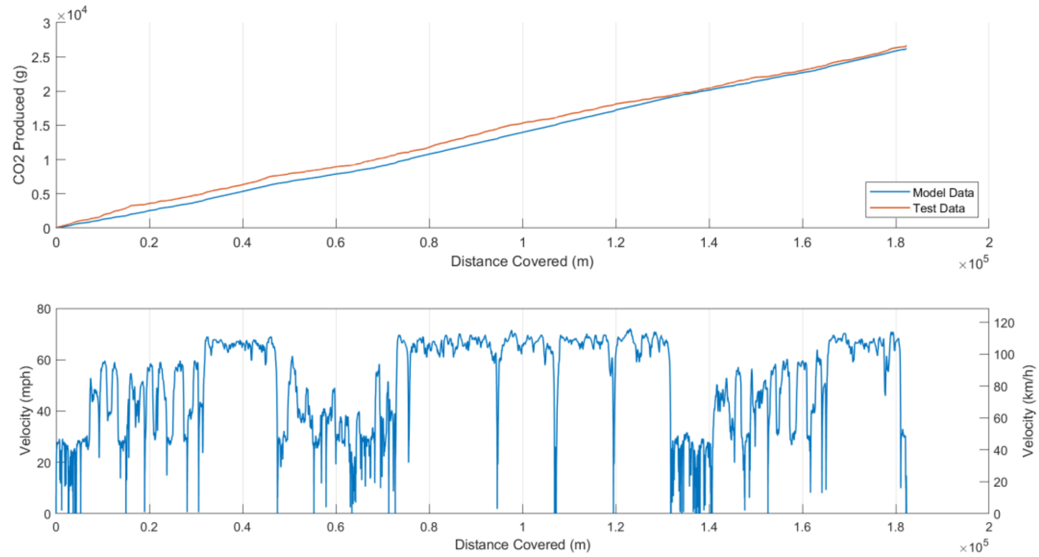

Figure 11. Real-world diesel CO2 emissions vs model predicted petrol CO2 emissions plotted as a function of distance covered.

The predicted CO_2 emissions agree well with the real-world data, with the total predicted CO_2 emissions over the journey of 26.2kg only 2% less than the total real-world CO_2 emissions of 26.7kg. The real-world emissions are initially higher than that of the predictions before later converging. Again this may be due to the engine being more inefficient when starting cold, which is not accounted for in the model. The real-world CO_2 emissions do not exhibit the same steps seen in the NO_x emissions, and overall the model simulated and real-world emissions profiles are very similar with both distance and time, validating this model as an accurate representation of vehicle dynamics and emissions.

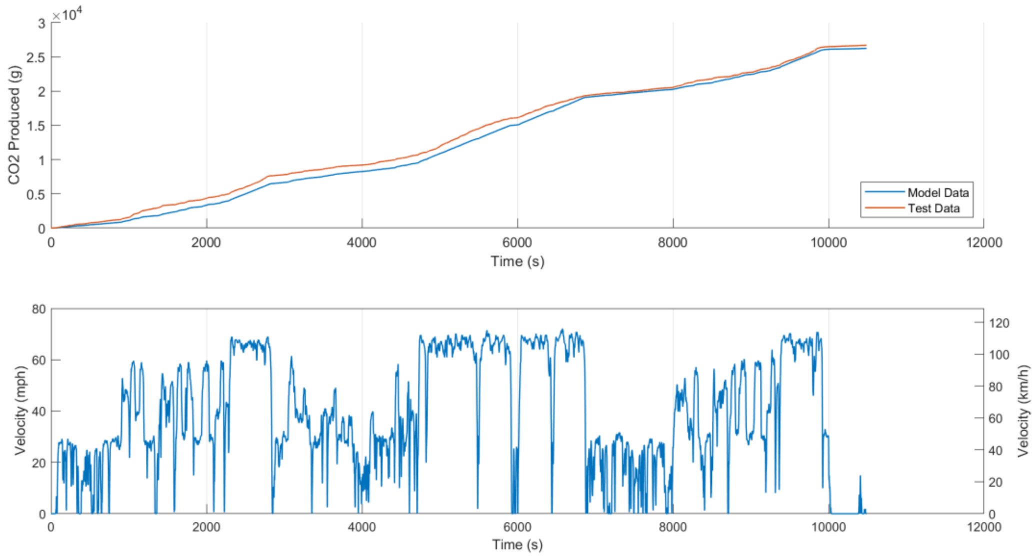

Figure 12. Real-world diesel CO_2 emissions vs model predicted petrol CO_2 emissions plotted as a function of elapsed time.

Results

Cruising at Speed Limit Simulation

As noted, it is a common misconception 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]. Whilst higher vehicle speeds mean the engine speed and torque required may fall into a more efficient part of the engine's brake specific fuel consumption map, the increase in energy required by the vehicle to accelerate to, and drive at these speeds have the opposite effect. 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). However, once up to speed it was also found that travelling at a constant speed of 20mph requires more fuel per unit distance travelled than travelling at 30mph due to the lower engine efficiency at the lower torque. 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 the Petrol Ford Focus, this distance is 0.91km, which is the shortest distance out of all the vehicles modelled. This efficiency cross-over distance also occurs at other speeds, as shown in Table 8 and Figure 13. In urban areas, particularly with other traffic on the road, it is typically not possible to travel even close to 0.91km without having to slow down or come to a stop due to junctions, pedestrian crossings or other vehicles, and in these cases, it is always more efficient for the Ford Focus to travel at 20mph than at 30mph.

Table 7. Energy required to accelerate to different speeds at a rate of 1.2m/s² 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)	2.1×10^5 J	-
25 mph (40.2 km/h)	3.1×10^5 J	148%
30 mph (48.3 km/h)	4.4×10^5 J	210%
35 mph (56.3 km/h)	6.0×10^5 J	286%
40 mph (64.4 km/h)	7.8×10^5 J	371%
45 mph (72.4 km/h)	9.9×10^5 J	471%
50 mph (80.5 km/h)	1.24×10^6 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)**
25 mph (40.2 km/h)	0.41 km
27.5 mph (44.3 km/h)	0.64 km
30 mph (48.3 km/h)	0.91 km
32.5 mph (52.3 km/h)	0.94 km
35 mph (56.3 km/h)	1.37 km
37.5 mph (60.4 km/h)	2.07 km
40 mph (64.4 km/h)	3.18 km
42.5 mph (68.4 km/h)	8.42 km

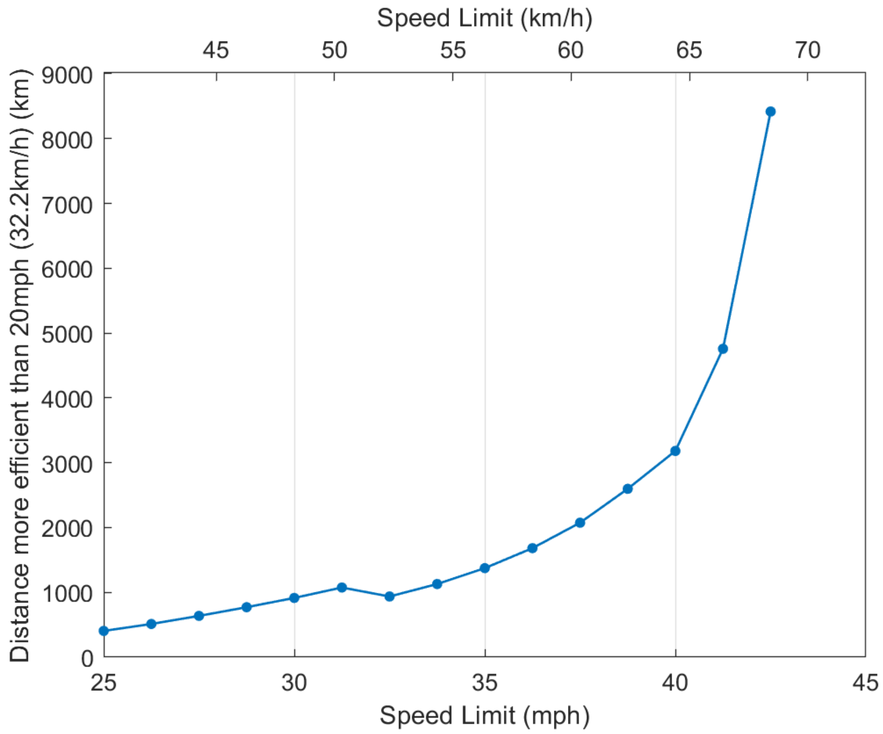

Figure 13. Travel distance required for different speed limits to be more efficient than travelling at 20mph (32.2km/h) for the simulated Ford Focus EcoBoost.

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) only if it accelerates and decelerates less than once every 1.30km, and the BMW X-5 only became more efficient at 30mph if it could maintain a constant speed for 3.08km, both of which are distances that are unlikely to be achieved in urban traffic conditions.

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 14 shows the velocity of vehicles at speed limits of 20mph and 30mph over one of the 50 simulated journeys. The dashed lines show the position of the traffic lights, and it can be seen that the vehicle sometimes stop due to a red light and at other times continue due to it being green. The distance to the nearest light when stopped can also be seen to vary. This is due to the differing number of vehicles ahead of the vehicle of interest when stopped at each set of lights. The simulated drive cycle is equivalent to 14 stop-start events over a 3km journey, which is taken to be reasonably representative of driving through London streets. Note that the model is based on every vehicle accelerating up to, and then maintain, the speed limit speed whenever there is space available, hence the artificial looking speed profile. In practice some drivers will do either more or less than 30mph in a 30mph speed limit, and many will exceed 20mph in a 20mph speed limit. This model does not attempt to consider each individual drivers behaviour; it models what the vehicle's emissions and efficiency will be if the vehicle is driven at each different speed limit.

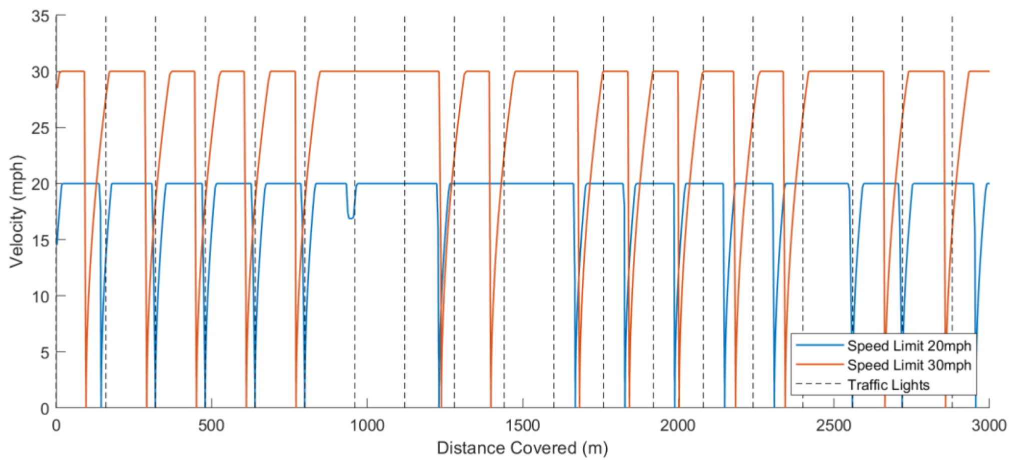

Figure 14. Example vehicle velocity over the modelled route at speed limits of 20mph (32.2km/h) and 30mph (48.3km/h).

Figure 15 shows the average time taken to travel 3km and Figure 16 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 25mph (40.2km/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. Driving faster just means the vehicle spends longer waiting at the next set of lights. The improvements in average speed of travel are more at speed limits below 30mph, but still very non-linear with respect to peak speed. At a speed limit of 30mph, the average speed is only 7.6% greater than at a speed limit of 20mph (32.2km/h), despite the peak speed being 50% higher.

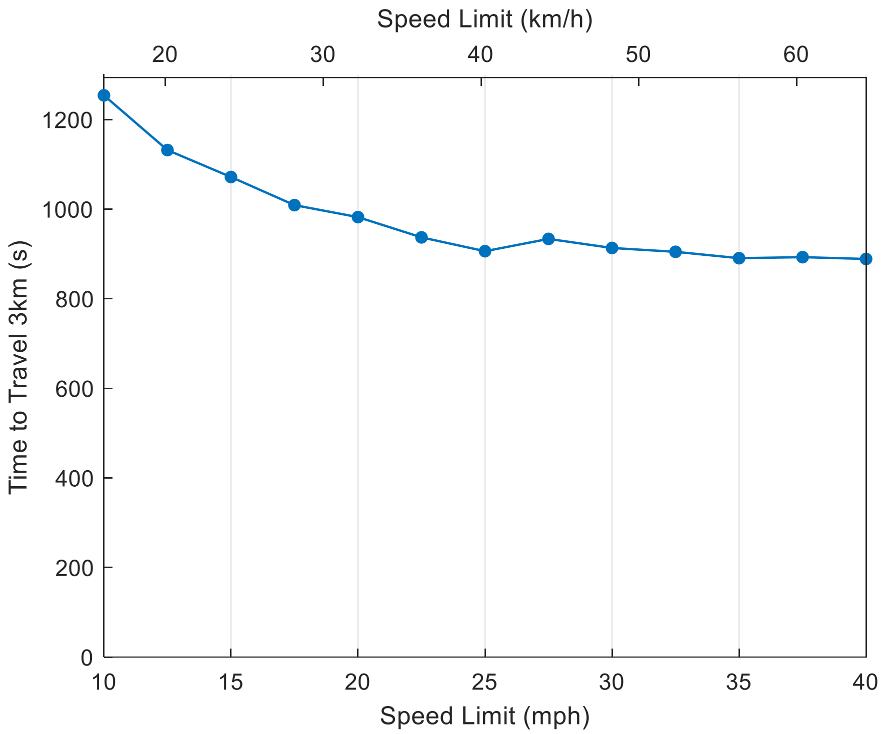

Figure 15. Average travel time of the simulated Ford Focus EcoBoost/TDCi over 3km for different speed limits.

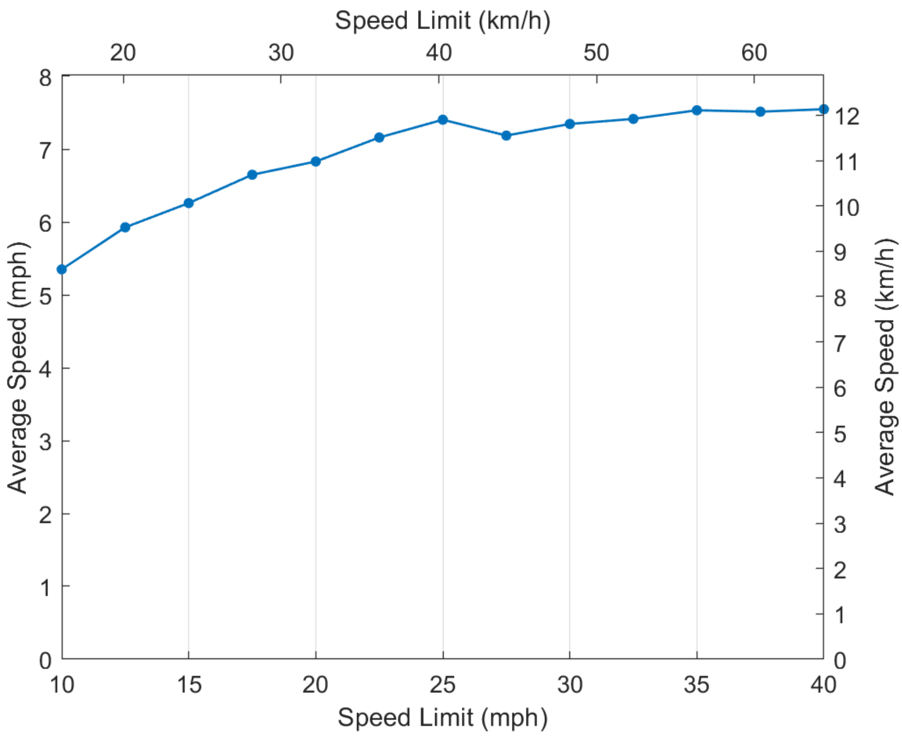

Figure 16. Average speed of the simulated Ford Focus EcoBoost/TDCi for different speed limits.

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 7.40mph (11.91km/h), which shows this model is representative of traffic in cities like London.

Figure 17 shows the CO_2 emissions and energy required for the simulated Ford Focus EcoBoost, whilst Figure 18 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. A real-world driver with a manual gearbox may change up to 3rd gear at 15mph cruise as they do not need the additional engine torque to accelerate further. An automatic gearbox is likely to behave as in the model, and remain in 2nd gear at 15mph, as it will have been calibrated to give the driver the additional power to accelerate beyond 15mph.

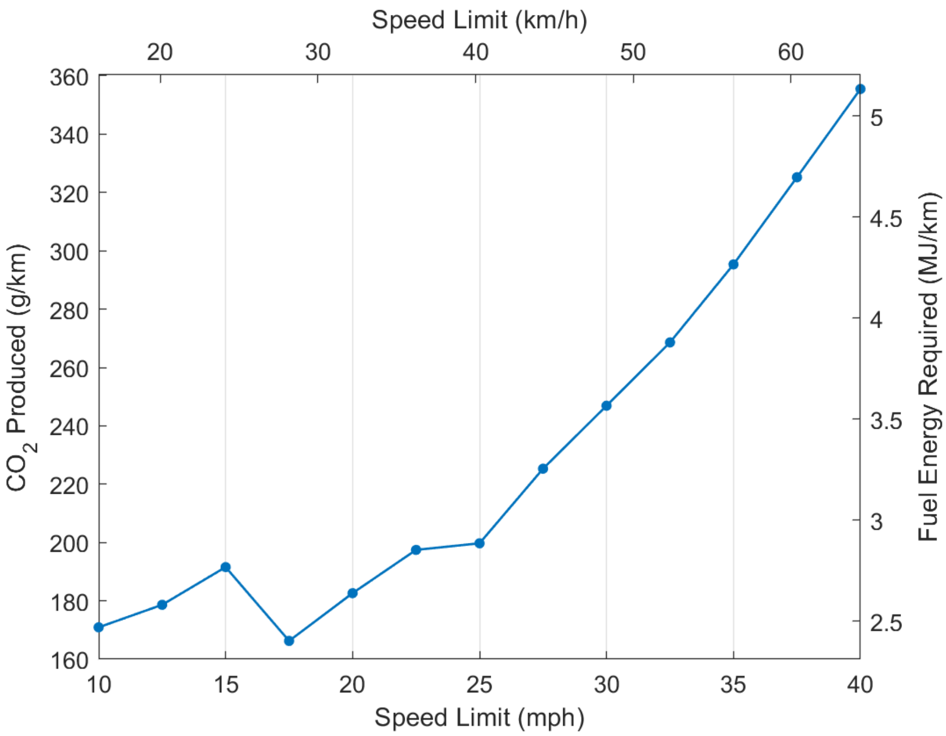

Figure 17. CO2 emissions and fuel energy required per kilometre travelled for a simulated 2016 Ford Focus EcoBoost.

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 35.9% more CO_2 emissions than travelling at a speed limit of 20mph, although Figure 16 shows that this only results in a 7.6% increase in average speed of travel. Travelling at a speed limit of 40mph (64.4km/h) results in a significantly greater 94.9% increase in CO_2 emissions relative to a speed limit of 20mph, for only a 10.5% 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 detrimental effect in terms of increased CO_2 emissions and fuel consumption.

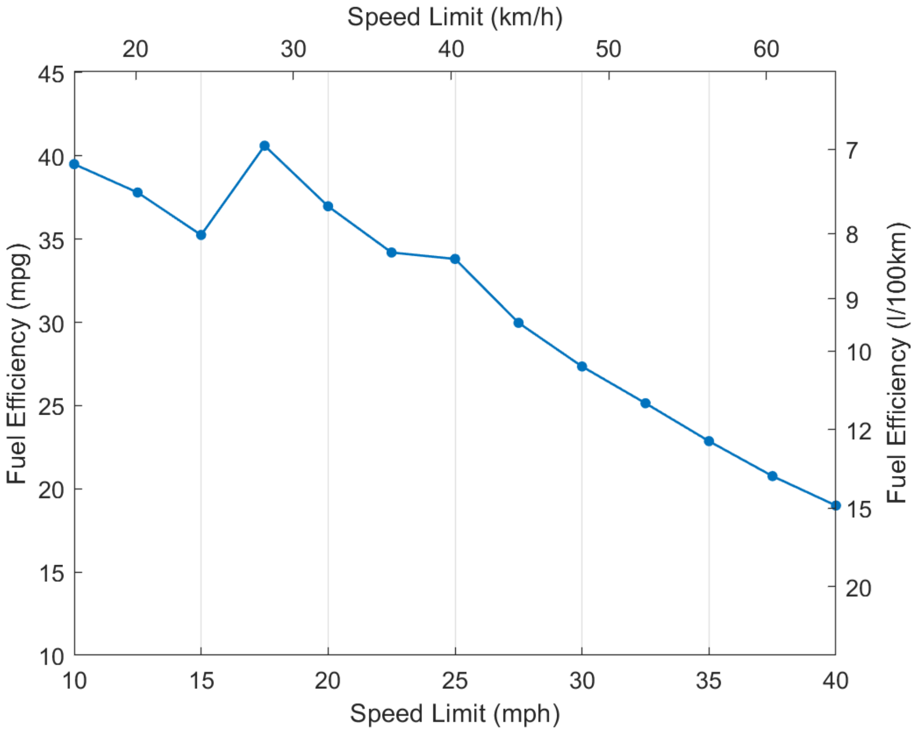

Figure 18. Fuel efficiency under urban traffic conditions for a simulated 2016 Ford Focus EcoBoost.

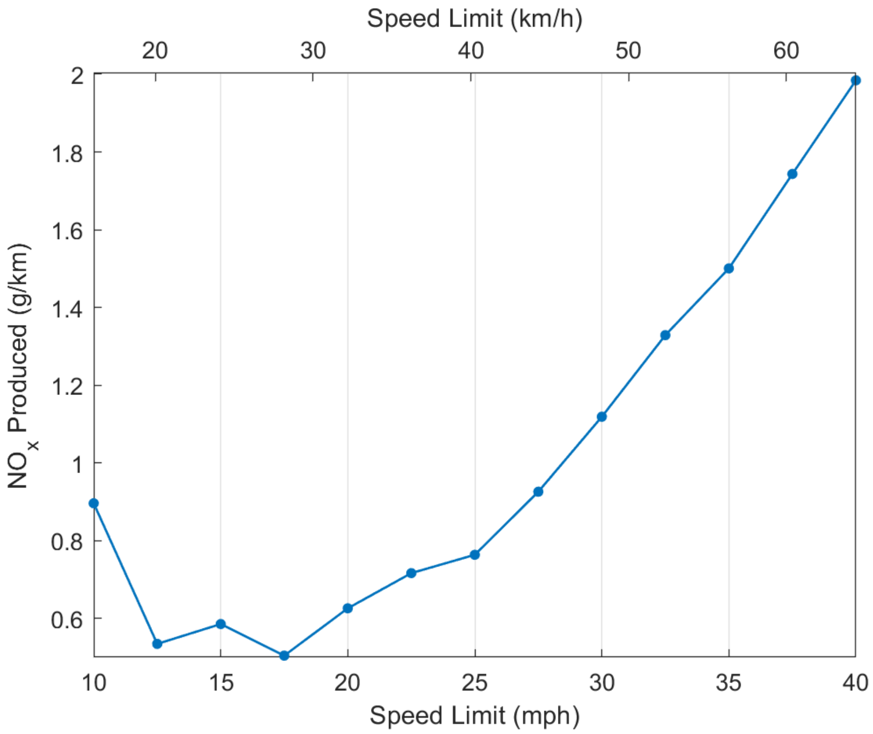

Figure 19. NOx emissions per kilometre travelled for a simulated 2016 Ford Focus TDCi.

The NO_x emissions from the simulated Ford Focus TDCi are shown in Figure 19. The NO_x emissions exhibit a similar relationship to speed limit as the CO_2 emissions in Figure 17, with a sharp increase at speed limits above 20mph (32.2km/h). 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 78.8% 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 217% 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 detrimental effect in terms of increased NO_x emissions.

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 20 shows the difference in the average speed attained by the vehicles for different speed limits and under different driving styles. Below speed limits of 20mph (32.2km/h), there is little increase in average speed attained for each driving style. Using the balanced rather than conservative driving style results in a 4.8% increase in average speed at a speed limit of 20mph, whilst using the aggressive driving style results in a 6.7% increase. Using the balanced rather than conservative driving style results in a 5.2% increase in average speed at a speed limit of 30mph (48.3km/h), whilst using the aggressive driving style results in a 8.9% increase.

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) if it were to stop at consecutive lights. 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 fuel energy required and CO_2 emissions when driving at different driving styles is shown in Figure 21. Both the difference in acceleration and up-shift thresholds have an impact of the emissions. An increase in acceleration creates an 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 22 by the lines tracing the brake specific fuel consumption at each gear when accelerating 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.

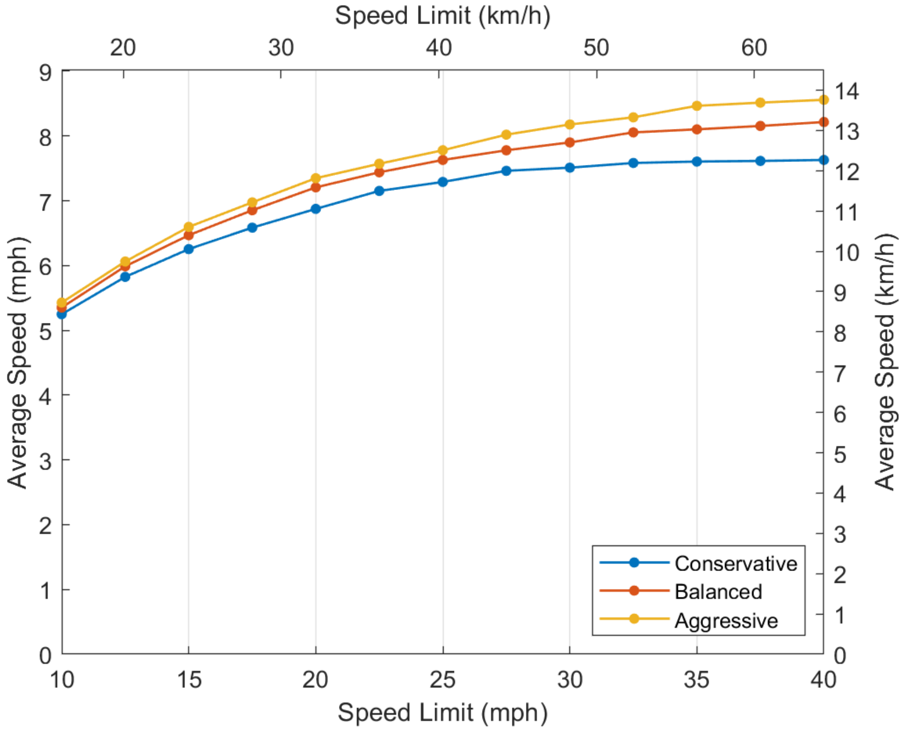

Figure 20. Average speed over the simulated journey for a 2016 Ford Focus EcoBoost at different driving style.

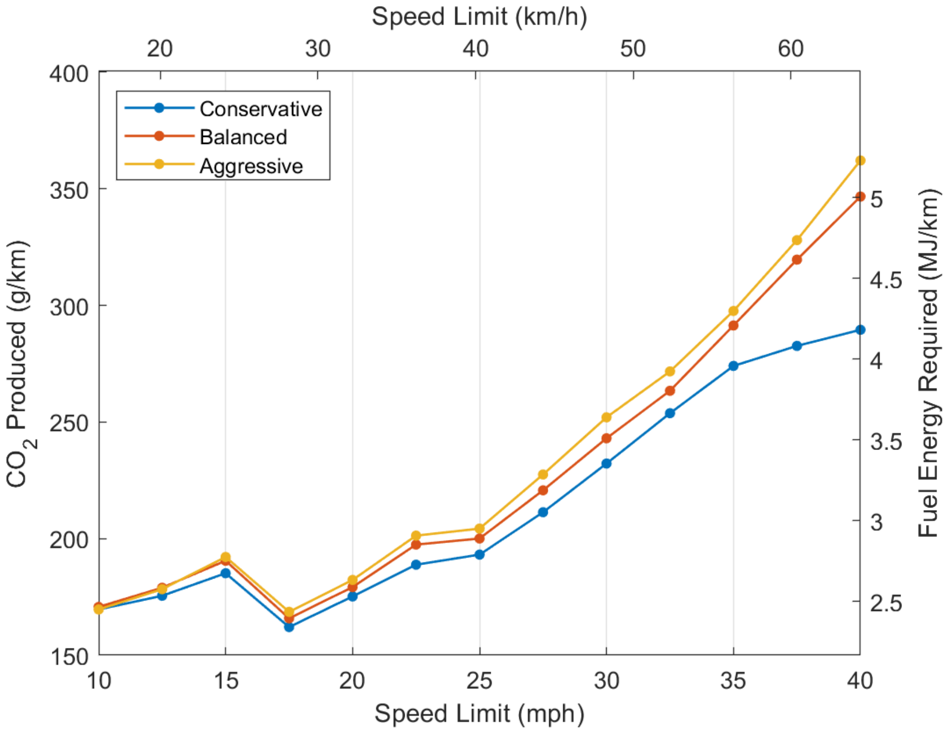

Figure 21. CO2 emissions and fuel energy required per kilometre travelled for a simulated 2016 Ford Focus EcoBoost at different driving style.

Below 35mph (56.3km/h), all three driving styles result in similar emissions, with the conservative driving style being only slightly more efficient. Using the conservative driving style requires 4.7% less fuel than the balanced driving style at a speed limit of 30mph (48.3km/h), whilst it requires 8.5% 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, 32.5% 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 20, 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.

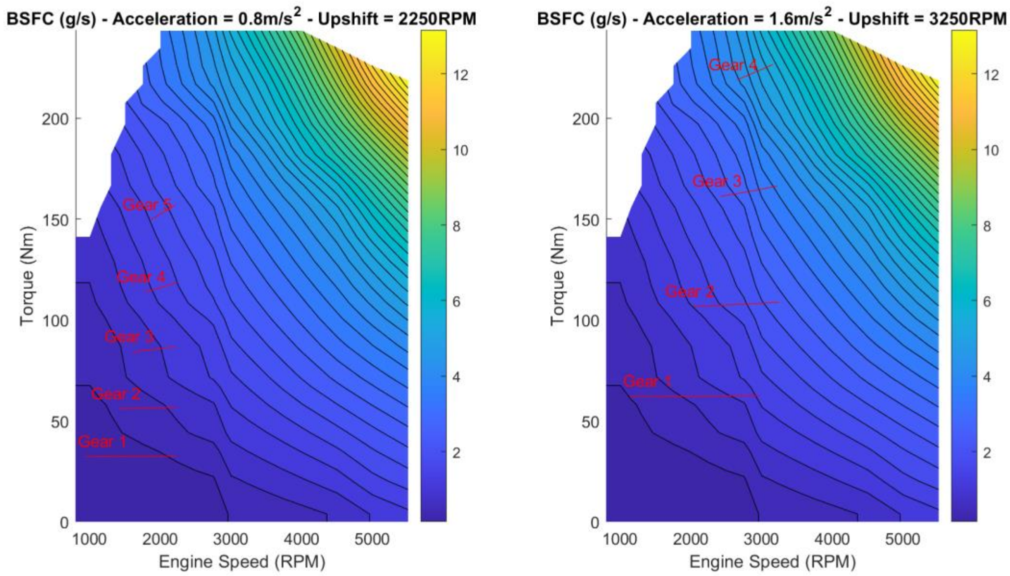

Figure 22. Brake specific fuel consumption for conservative and aggressive driving styles for a simulated 2016 Ford Focus EcoBoost whilst accelerating.

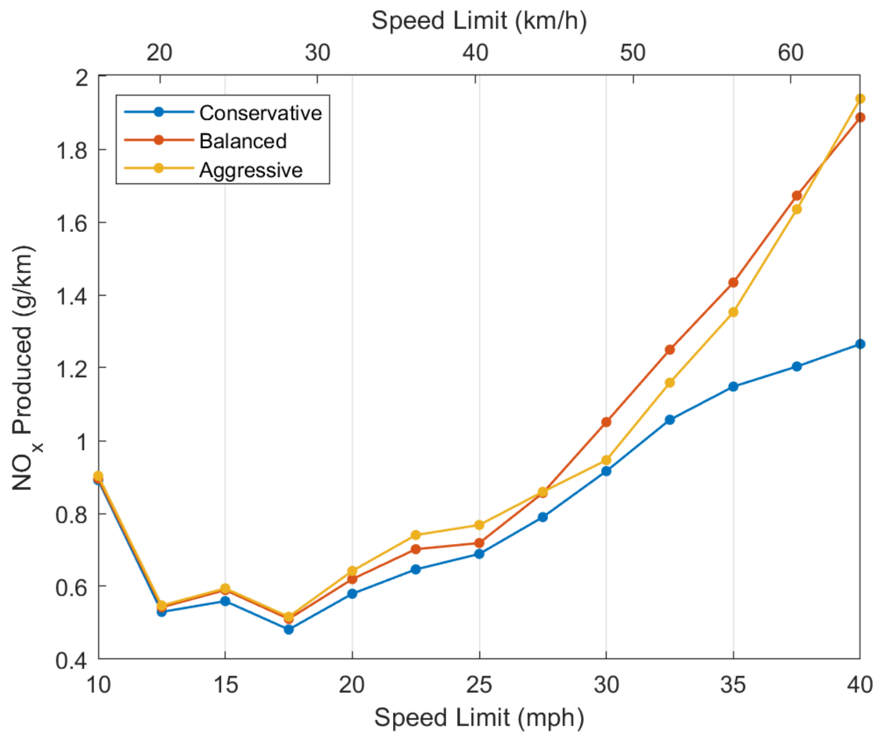

Figure 23. NOx emissions per kilometre travelled for a simulated 2016 Ford Focus TDCi at different driving style.

Similar relationships can be seen in the NO_x emissions shown in Figure 23. Using the conservative driving style at a speed limit of 20mph (32.2km/h) results in 6.9% fewer NO_x emissions relative to the balanced driving style and 10.8% 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 69.5% 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 9.6% increase in average speed.

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 24 and for the same journey, it can be seen that the Mazda CX-9 is considerably more inefficient than the Ford Focus. The Mazda CX-9 requires 58.7% more energy to complete the same journey at a speed limit of 30mph (48.3km/h), resulting in a fuel efficiency of 16.9mpg (13.9 l/100km) in comparison to the Ford Focus's fuel efficiency of 27.5mpg (8.5 l/100km). At 20mph (32.2km/h) the Mazda CX-9 requires 62.1% more energy, resulting in a fuel efficiency of 22.6mpg (10.4 l/100km) in comparison to the Ford Focus's fuel efficiency of 37.0mpg (6.4 l/100km). 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 the larger Mazda CX-9.

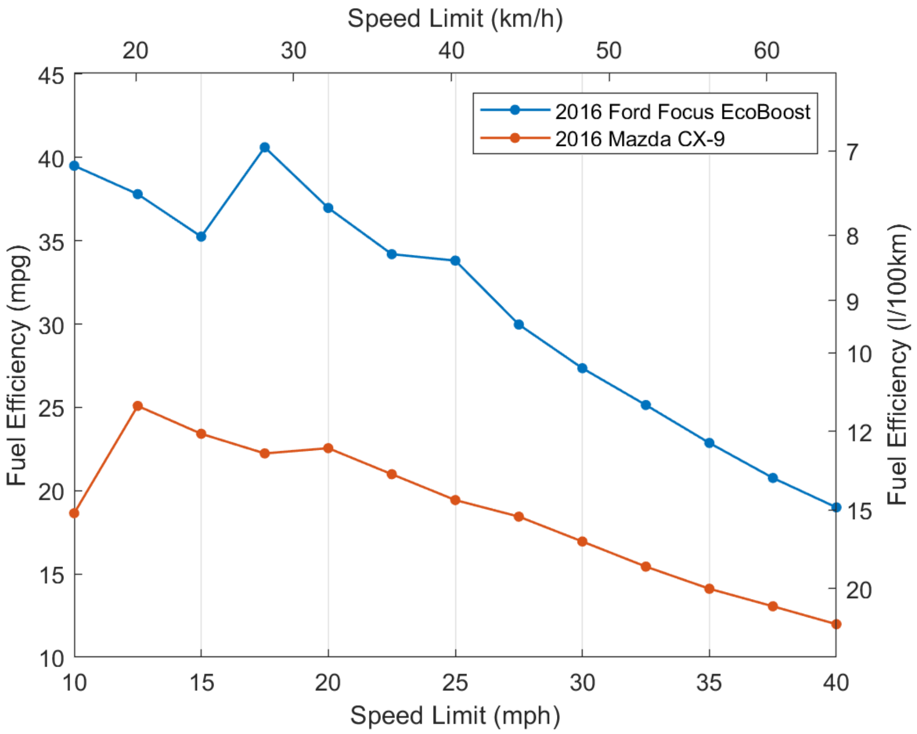

Figure 24. Fuel efficiency under urban traffic conditions for a simulated 2016 Ford Focus EcoBoost and 2016 Mazda CX-9.

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.

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 with a 3.0l BMW N57 diesel engine. This vehicle is of a similar size and mass to the modelled petrol engine Mazda CX-9

The difference in energy required at different speed limits for the two vehicles can be seen in Figure 25. Below 20mph, both vehicles require a similar amount of energy, but above 20mph 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 9.0% 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 5.2% more energy.

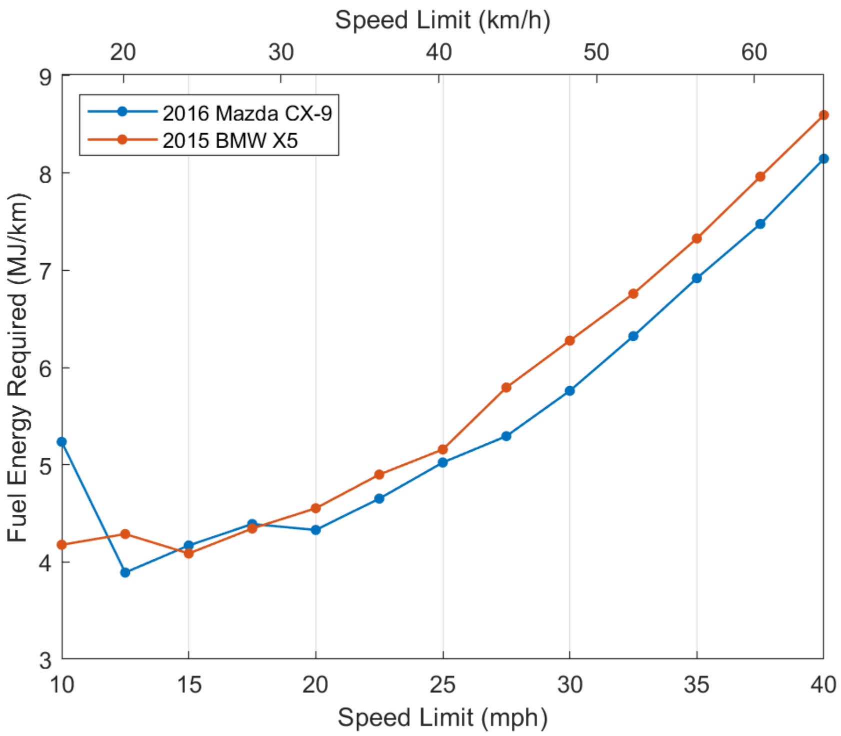

Figure 25. Fuel energy required for a simulated 2016 Mazda CX-9 (petrol) and 2015 BMW X5 (diesel).

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 or l/100km. This can be seen in Figure 26. 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 27. This plot follows much the same shape as the plot of energy required shown in Figure 23, despite the differences in the fuel. At a speed limit of 30mph (48.3km/h) the Mazda CX-9 produces 7.3% 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 3.5%. 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.

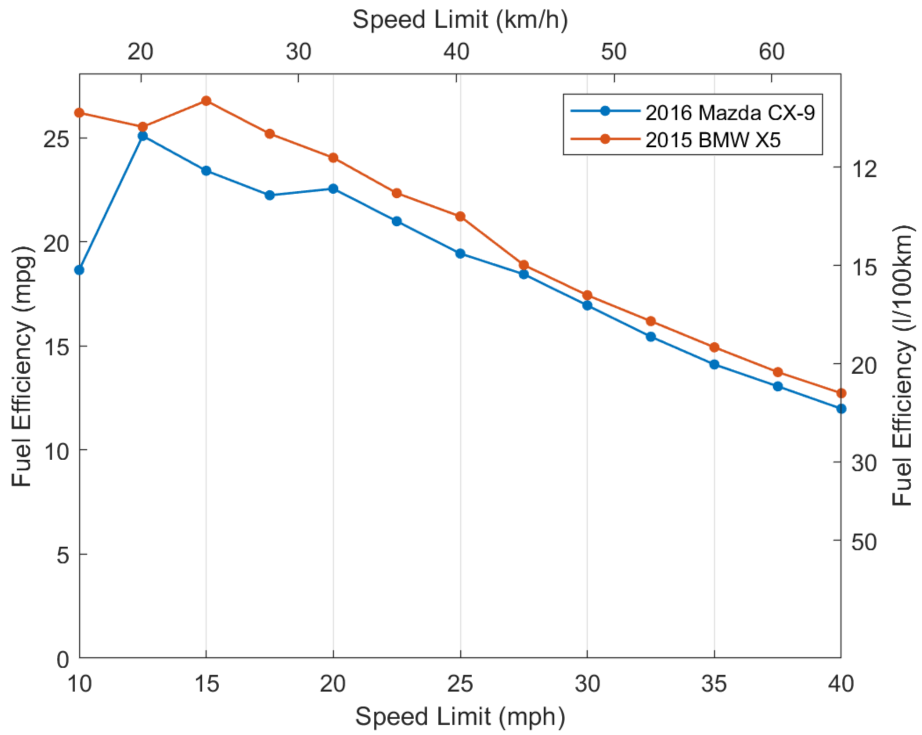

Figure 26. Fuel efficiency for a simulated 2016 Mazda CX-9 (petrol) and 2015 BMW X5 (diesel).

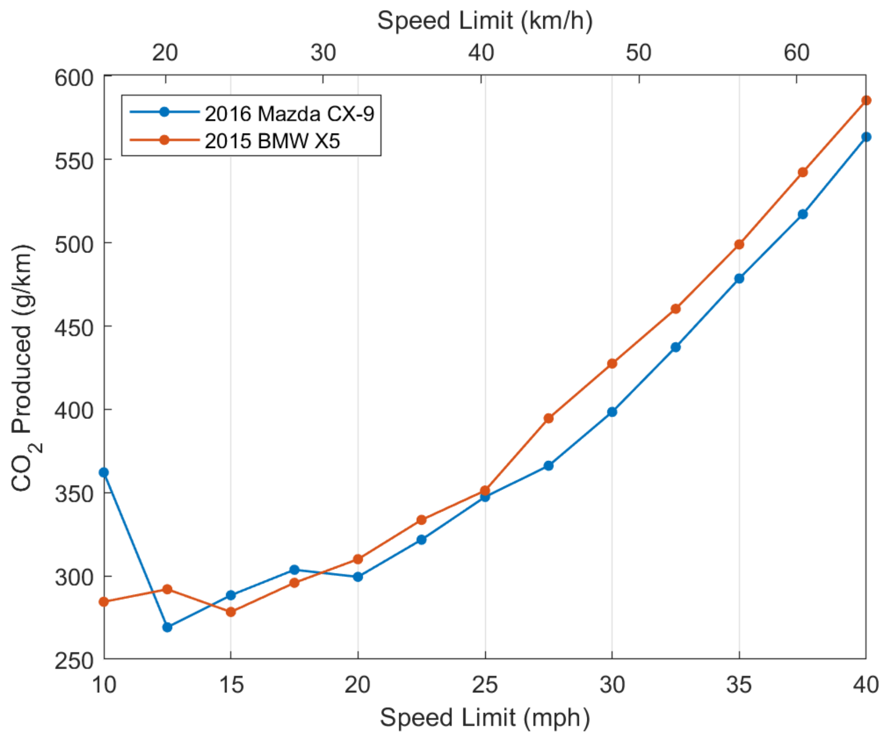

Figure 27. CO2 emissions for a simulated 2016 Mazda CX-9 (petrol) and 2015 BMW X5 (diesel).

Figure 28 shows the comparison in fuel efficiency of the three modelled vehicles; the Ford Focus, Mazda CX-9 and BMW X5. These are also compared to the real-world measured fuel efficiencies of two vehicles, a 2007 Toyota Verso 2.2D (diesel) and a 2014 Ford B-Max Zetec Auto (petrol). The fuel efficiency was measured using the car's trip computer over a distance of approximately 3 miles, and with stop/starts approximately every 220m. The measured fuel efficiency of the Ford B-Max is slightly better than the two SUVs, whereas the measured fuel efficiency of the Toyota Verso is slightly worse than the Ford Focus petrol. Both measured fuel efficiencies also follow the same relative change in efficiency as a function of peak speed as seen in the simulations, and the fuel efficiency also peaks at 15 to 20mph. This also helps to validate the model as being representative of urban driving conditions.

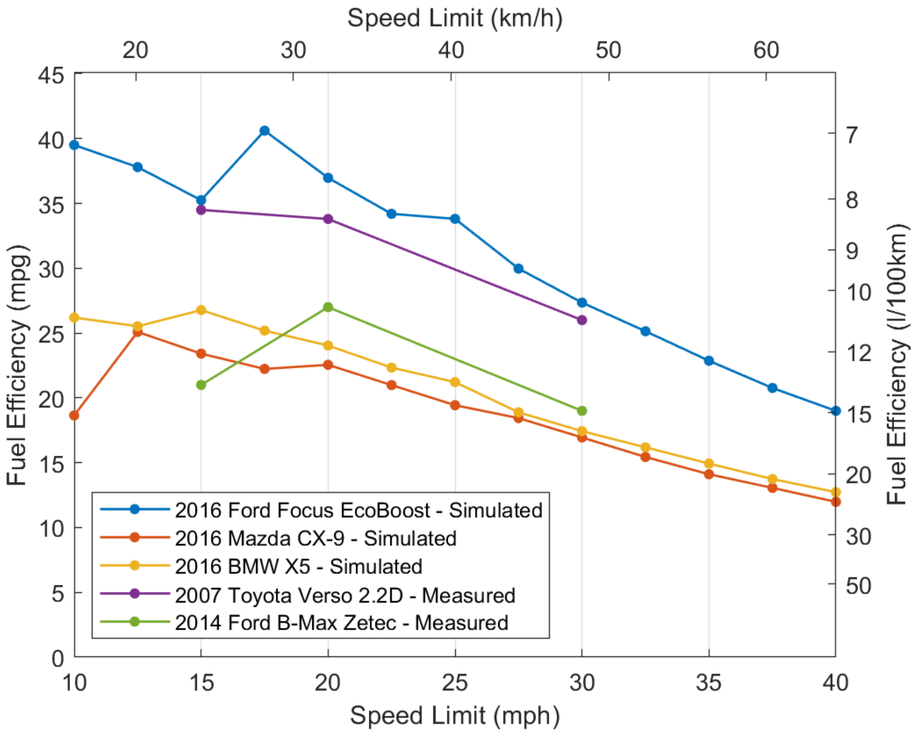

Figure 28. Comparison of simulated fuel efficiencies of a 2016 Ford Focus (petrol), 2016 Mazda CX-9 (petrol) and 2015 BMW X5 (diesel) to the measured fuel efficiencies of a 2007 Toyota Verso (diesel) and 2014 Ford B-Max Zetec (petrol).

Electric Vehicle Energy Efficiency

The traffic simulator was also used to model the efficiency of a Nissan Leaf Battery Electric Vehicle (BEV). Apart from a fixed parasitic load from the electronics and infotainment systems, BEVs do not get more efficient as vehicle speed increases. A more in-depth analysis of different BEV performance will be included in a future paper. A summary of the findings for the Leaf on the simulated traffic drive cycle as a function of speed limit is shown in Figure 29.

The Nissan Leaf consumed 0.30 MJ/km (135 Wh/mile) and emitted 15.2 g/km of CO_2 at a 15mph top speed, based on charging at the UK average grid intensity of 180g CO_2/kWh. At 20mph this increased by 33% to 0.40 MJ/km (179 Wh/mile), and 20.1 g/km of CO_2. Increase the speed limit to 30mph, and the emissions rise by a further 65% to 0.66 MJ/km (295 Wh/mile), and 33.2 g/km of CO_2, more than double those at a 15mph limit. For comparison, the CO_2 reduction gained by slowing one BMW X5 from 30mph peak speed to 20mph peak speed, of 117g over 1km, is approximately the same as the CO_2 emissions from charging six Nissan Leaf to drive the same distance.

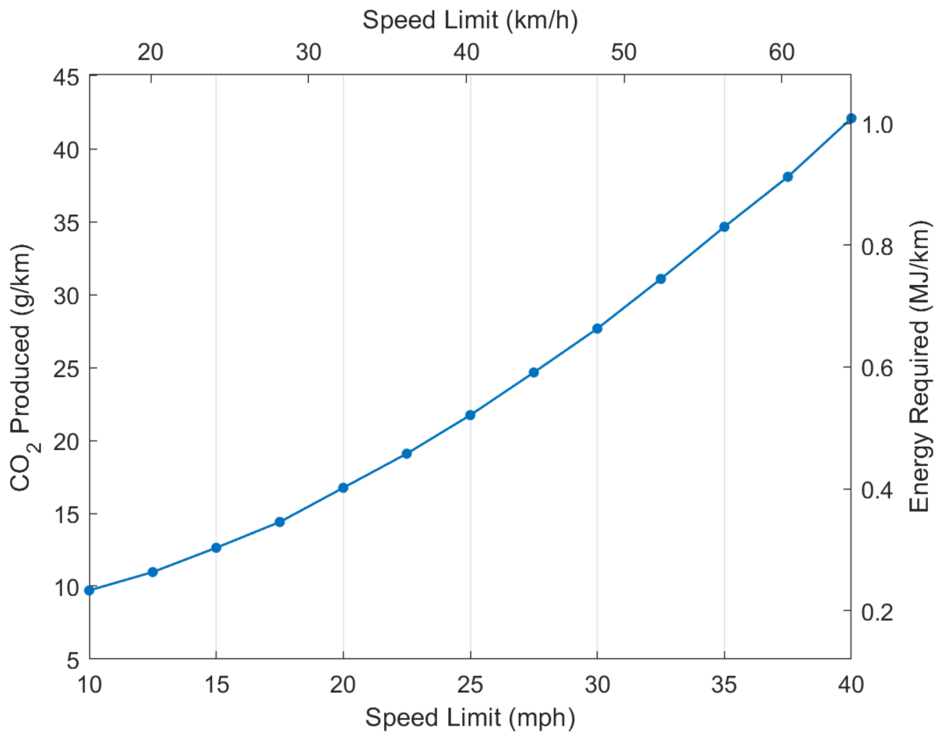

Figure 29. Nissan Leaf BEV energy consumption and CO2 emissions as a function of speed limi, based on a grid intensity of 180g/kWh.

Table 11 shows a summary of the most efficient speeds in traffic for different simulated vehicles. This speed varies from vehicle to vehicle, but always falls in the range of 10 to 20mph (16.1 to 32.2km/h).

Table 11. Most efficient peak speed in traffic for different simulated vehicles.

	Most Efficient Peak Speed in Traffic (mph)
Ford Focus EcoBoost	17.5
BMW X5	15
Mazda CX-9	12.5
Nissan Leaf BEV	<10
Toyota Verso 2.2D	15
Ford B-Max Auto	20

Simulated WLTP Drive Cycle

The WLTP was simulated with the four modelled internal combustion engine vehicles. The fuel consumption was calculated over this simulated journey and is shown in Figure 30. It was found that that the two hatchbacks, the Ford Focus EcoBoost and Ford Focus TDCi, require a similar amount of energy to complete the journey, but this results in different fuel consumptions profiles because of differences in the calorific density of petrol and diesel. Their fuel efficiencies are 39.6mpg (5.9 l/100km) and 47.7mpg (4.9 l/100km) for the Ford Focus EcoBoost and Ford Focus TDCi respectively. The two SUVs, the Mazda CX-9 and the BMW X-5, show a similar relationship, in that the energy required is similar, but their fuel efficiencies are 24.6mpg (9.6 l/100km) and 27.7mpg (8.5 l/100km) respectively.

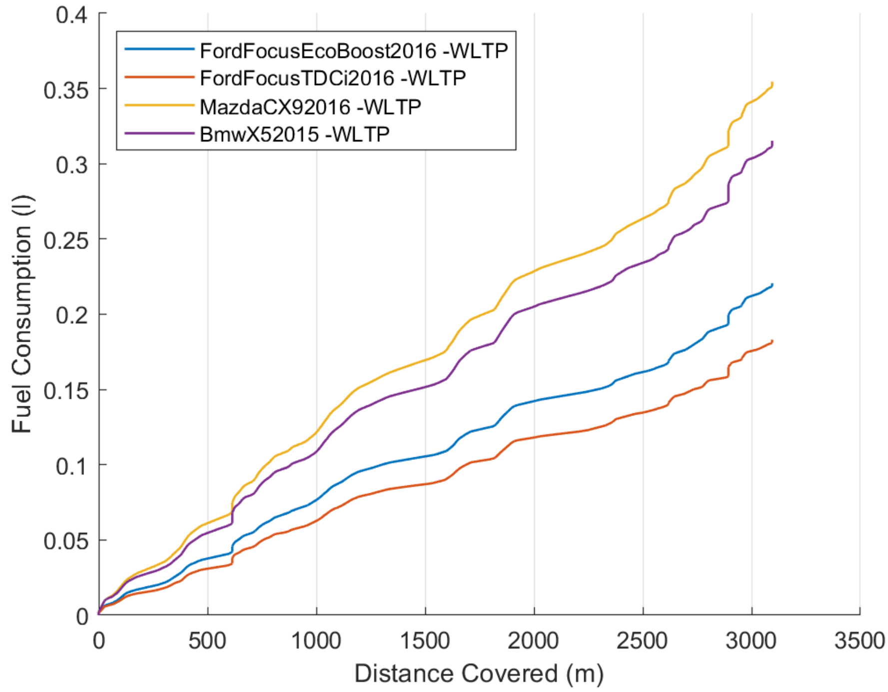

Figure 30. Comparison of fuel consumption to complete the simulated WLTP for a Ford Focus EcoBoost (petrol), Ford Focus TDCi (diesel), Mazda CX-9 (petrol) and BMW X5 (diesel).

Adapted versions of the WLTP were also simulated. These adapted versions were limited to different maximum speeds, but with the distance extended while limited such that the distance covered over the limited period is the same as the distance covered when not limited. This means that the total distance covered for each adapted version is the same, and this allows for a fair comparison.

The fuel required by the simulated Ford Focus EcoBoost over the original WLTP and three adapted versions limited to 30mph (48.3km/h), 20mph (32.2km/h) and 15mph (24.1km/h) can be seen in Figure 31. There is little difference in the simulated fuel consumption between the original and version limited to 30mph. This is because the WLTP only exceeds 30mph briefly after 1155m. This is where the 2 profiles diverge as the original WLTP uses more fuel at this slightly higher speed. Over the full journey, this results in 1.2% more fuel consumption. The largest difference is between the original version and adapted version limited to 20mph. Over this journey, 11.0% more fuel is consumed over the WLTP cycle compared to the same trip limited to 20mph. Similarly, being limited to 30mph rather than 20mph requires an additional 9.7% of fuel. 4.3% more fuel is required when limited to 15mph is relative to when limited to 20mph, but as discussed in previous sections, this is because at 20mph the vehicle is in 3rd gear, whereas at 15mph the vehicle is still in 2nd gear and at a more inefficient point in the BSFC map.

The fuel required by the simulated BMW X5 over the original WLTP and three adapted versions limited to 30mph (48.3km/h), 20mph (32.2km/h) and 15mph (24.1km/h) can be seen in Figure 32. The difference between the different speed limits is greater than the difference seen in the simulation Ford Focus EcoBoost. Permitting the vehicle speed to go up to 30mph rather than 20mph increases the fuel consumed, and CO2 emitted, by 15.0%. Driving at up to 20mph rather than 15mph increases both by 4.9%.

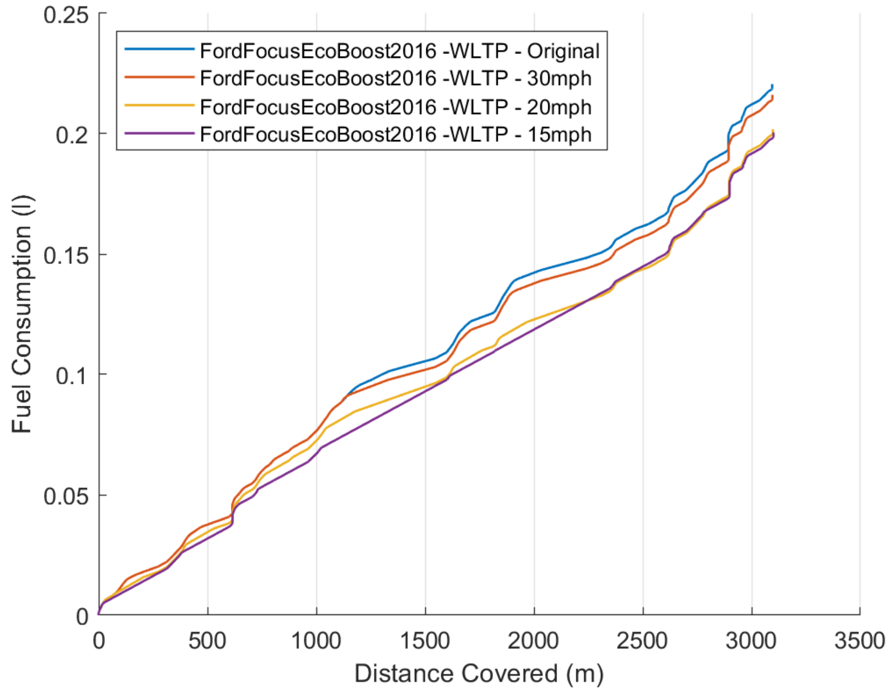

Figure 31. Comparison of fuel consumption for a simulated Ford Focus EcoBoost to complete the original WLTP and three different adapted versions of the WLTP, limited to maximum speeds of 30mph (48.3km/h), 20mph (32.2km/h) and 15mph (24.1km/h).

The WLTP is a standard method for comparing the differences in fuel efficiency and emissions between different vehicles used by the automotive industry. However, there is a noticeable difference in fuel consumption between speed limits of 20mph (32.2km/h) and 30mph (48.3km/h) for the traffic simulations and the WLTP simulations. In the traffic simulations, a 30mph speed limit required 35.9% more fuel, whereas in the WLTP simulations only 9.7% more fuel was consumed. This is because the WLTP is not representative of the urban traffic modelled as part of this investigation. The average speed over the WLTP is 11.7mph (18.8km/h), compared to 7.4mph for the traffic simulations, which is the same as the TfL published average speed in London [5]. This can also be seen in the number of stops during the journey. The WLTP, as shown in Figure 8, features only 3 stops over about 3km, and includes a section where the vehicle covers 2km without having to come to a stop, something that most UK city drivers can only dream of. A GPS log of a real-world drive across London on a mix of main roads and residential streets, taken at 8am on a weekday, typical of a school run or a commute, is shown below.

Over the 5.3km journey, the vehicle drops below 10mph and then accelerates back up to the speed limit approximately 23 times, or once every 230 metres. Note that whilst the traffic simulator shows approximately the same number of acceleration/deceleration events, the simulator shows the vehicle coming to a complete stop. However, because the energy required to accelerate from 10 to 30 mph is $(30^2-10^2)/(30^2)$, or 89% of the energy required to accelerate from 0 to 30 mph, the difference due to the real-world driver maintaining some momentum at the junctions will be minimal.

The WLTP is therefore not representative of driving in most urban streets. The example traffic simulation journey in Figure 14 has 14 stops over the same distance as the WLTP. This means that there are fewer periods of acceleration which were previously shown to be the main contributor to the differences seen in fuel consumption and emissions at different speed limits.

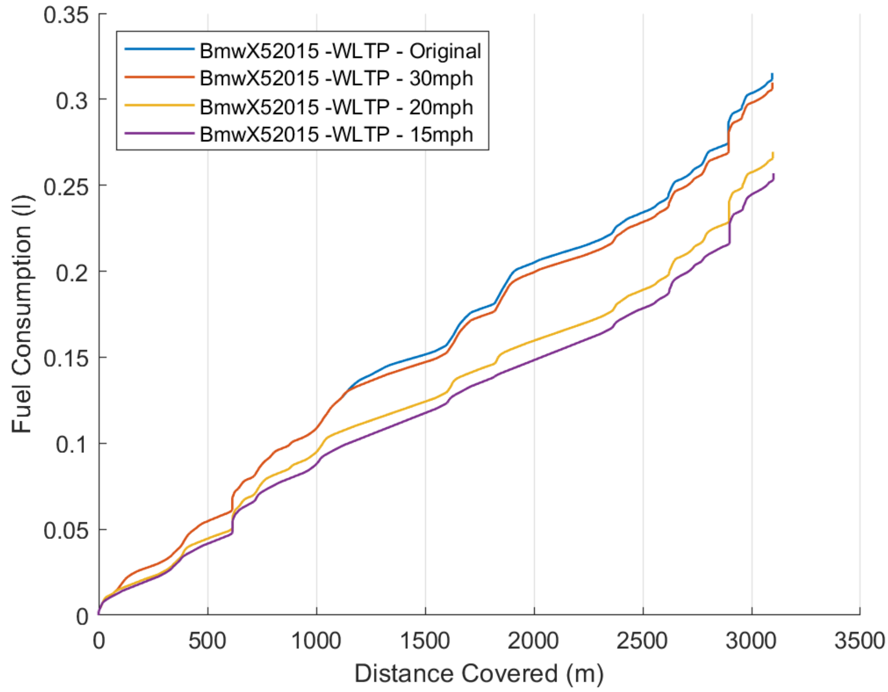

Figure 32. Fuel consumption for a simulated BMW X5 to complete the original WLTP and three different adapted versions of the WLTP, limited to maximum speeds of 30mph (48.3km/h), 20mph (32.2km/h) and 15mph (24.1km/h).

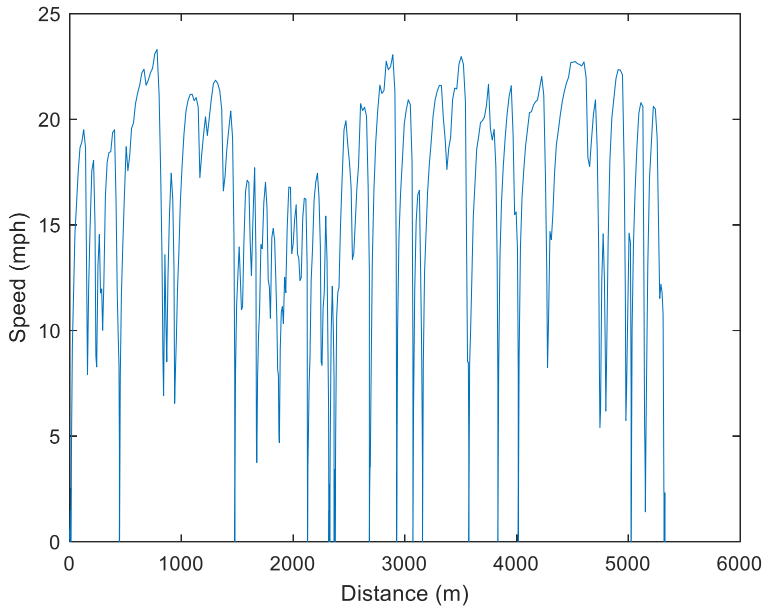

Figure 33 Real-world city driving speed profile representative of a city commute or school run in London, UK.

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 7.4mph (11.9km/h), which is the same as 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 0.91km without stopping, which is unlikely under urban driving conditions. At 40mph (64.4km/h), this distance increases to 3.18km. At a speed of 30mph rather than 20mph, the modelled Mazda CX-9 is only more efficient if stopping less than once every 1.30km, and the modelled BMW X5 is only more efficient after 3.08km. For an environmentally conscious traffic authority, this means that all roads with any junctions, side roads or crossings more frequent that once every 0.91-1.3km would expect to get lower emissions with a well enforced speed limit of 20mph (32.2km/h) rather than 30mph (48.3km/h). Note that although this investigation only modelled cars, the reduction in emissions scales with the laden vehicle weight. Light commercials and heavy-duty vehicles would therefore be expected to see even larger reductions in emissions at 20mph versus 30mph.

Under the modelled urban traffic conditions, it was found that for a given traffic density, there was only a small reduction in journey times when increasing peak vehicle speeds from 15mph to 25mph, and virtually no reduction in journey times when increasing vehicle speeds beyond 25mph. For the Ford Focus EcoBoost it was found that a speed limit of 30mph results in 35.9% more CO_2 emissions and 78.8% more NO_x emissions than travelling at a speed limit of 20mph, for only a 7.6% increase in average speed of travel. Fuel efficiency follows the same trend, resulting in an efficiency of 27.4mpg (8.6 l/100km) at 30mph, and 37.0mpg (6.4 l/100km) at 20mph.

An unanticipated result found whilst developing the traffic simulator was that one of the main factors affecting average speed, and hence urban journey times, was vehicle size. Urban journey time is primarily a function of the time spent waiting at each junction. This in turn is a function of the size of the vehicles on the road. More small vehicles can pass through a given green light in a fixed time than can longer vehicles, because they are more densely packed. This means traffic queues would move faster, and journey times would reduce significantly, if we all drove smaller vehicles.

Different driving styles were modelled, and it was found that an aggressive driving style resulted in a 8.5% 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. The CX-9 required 58.7% more energy than the Ford Focus hatchback to travel at a speed limit of 30mph under the modelled urban traffic conditions.

The modelled diesel engine BMW X5 SUV performed similarly to the petrol engine Mazda CX-9. These vehicles had similar fuel efficiencies, and although they had fewer CO_2 emissions, the NO_x emissions of the diesel vehicle are likely considerably larger, although this was not modelled here.

Simulating the WLTP is an effective means of showing how vehicle size impacts the fuel efficiency and emissions of different vehicles. Adapting the test procedure to account for different speed limits was not as effective at illustrating the true difference in fuel efficiency and emissions under dense urban traffic conditions because the limited stop/starts of the WLTP are not representative of such conditions.

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