An evaluation of the estimated impacts on vehicle emissions of a 20mph speed restriction in central London

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FINAL REPORT

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EXECUTIVE SUMMARY

This report details research work undertaken in the first quarter of 2013 to address the question of the environmental impacts of 20mph restrictions in central London. Average speed models suggest that a lower speed limit in urban areas may result in higher pollutant emissions. However, the stop-start nature of traffic in central London means that such a method may not be suitable, and further investigation is required.

The following objectives were addressed:

1. The difference in driving styles between 20mph and 30mph roads
2. The impact of this change on estimated tailpipe emissions of NO_X, PM_{10} and CO_2
3. The impact on emissions of different methods of speed control on urban roads
4. The impact on emissions from brake and tyre wear of a 20mph zone

METHODOLOGY AND DATA COLLECTION

The primary data set for this research is a series of vehicle trajectories, measured with the use of high-grade GPS equipment. Data regarding time, speed and position were recorded at a frequency of 1Hz, alongside information regarding precision. Several routes across central London were chosen in order to cover a range of traffic conditions. The sites chosen are shown below:

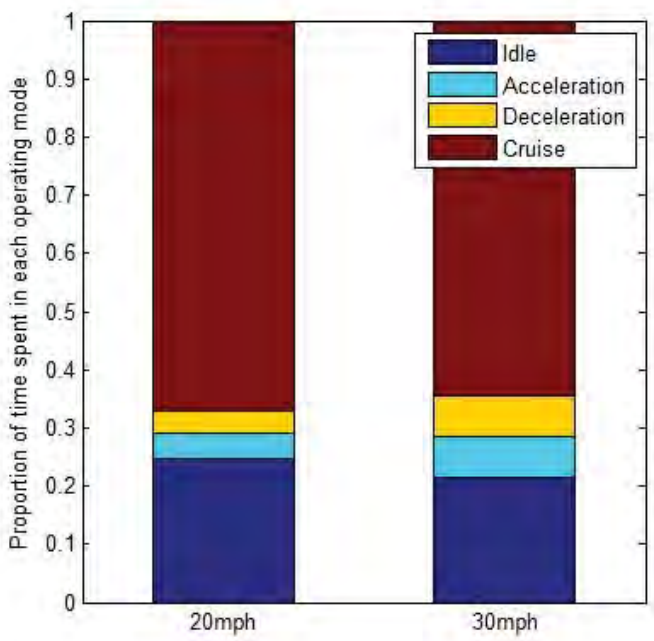
Route	Length (miles)	Borough	Streets (abridged)
A	2.0	City of London	London Wall, Houndsditch, Aldgate, High Street, Bishopsgate, Threadneedle Street, Gresham Street
B	2.1	Islington	Liverpool Road, Holloway Road, Upper Street, Cross Street, Essex Road, Islington Park Street
C	2.3	Camden	Camden High Street, Kentish Town Road, St Pancras Way, Royal College Street, Camden Street
D	2.0	Southwark / Lambeth	The Cut, Baylis Road, Westminster Bridge Road, Borough Road Marshalsea Road, Union Street
E	2.4	Westminster	Vauxhall Bridge Road, John Islip Street, Horseferry Road, Buckingham Gate
F	2.7	Kensington & Chelsea / Westminster	Exhibition Road, Queen’s Gate, Onslow Gardens, Old Church Street

Eight days were spent collecting data over a period of approximately three weeks in January and February 2013. This covered a range of days and time of day. Each route was repeated multiple times to provide a series of observations (laps). The number of laps for each route ranged between 12 and 27. The minimum amount of data collected for a single route was 170 minutes.

DRIVING STYLES ON 20MPH ROADS

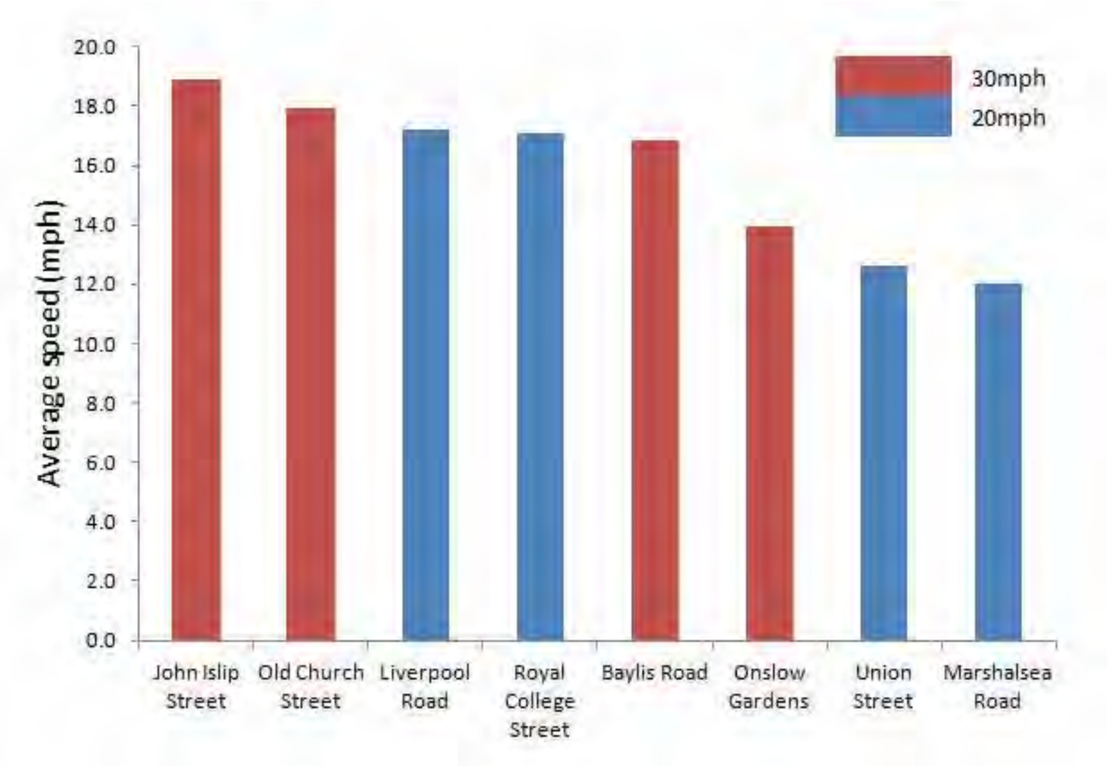
Post-processing was undertaken to split each route into a series of segments (38 in total over all routes). Each segment has a particular set of characteristics associated with it, such as a 20mph or 30mph speed limit. An example of this segmentation is shown below:

A greater range of vehicle speeds are seen on 30mph segments compared to 20mph segments. In addition, a greater proportion of time is spent in the acceleration and deceleration modes of vehicle operation on 30mph segments, as can be seen below. It is recognized that this could be a facet of study design and post-processing, rather than a particular characteristic of the type of road. By limiting the data to only the cruise mode of vehicle operation, the impact of junctions and queuing can be removed and some of these effects can be countered. For this part of the analysis, only data where the vehicle is travelling at a steady speed (greater than 5mph and with no significant acceleration or deceleration) will be considered. Restricting the data in this way shows lower average cruise speeds (both median and mean) and lower variation of speed (represented by standard deviation) on 20mph segments compared to 30mph segments. Mean cruise speeds were 14.9mph on 20mph segments and 19.2mph on 30mph segments. A test of statistical significance was conducted (Mann-Whitney *U* test) and it was concluded that the distributions were different.



It was therefore concluded that cruise speeds on 20mph and 30mph route segments are statistically different.

A site-specific analysis was also undertaken to ascertain any difference in observed driving styles on different categories of street. Several segments were identified as either “residential” or “non-residential”. No systematic difference could be seen regarding observations of driving style on these different route segments. For example, average speed on residential streets does not appear particularly related to speed limit:



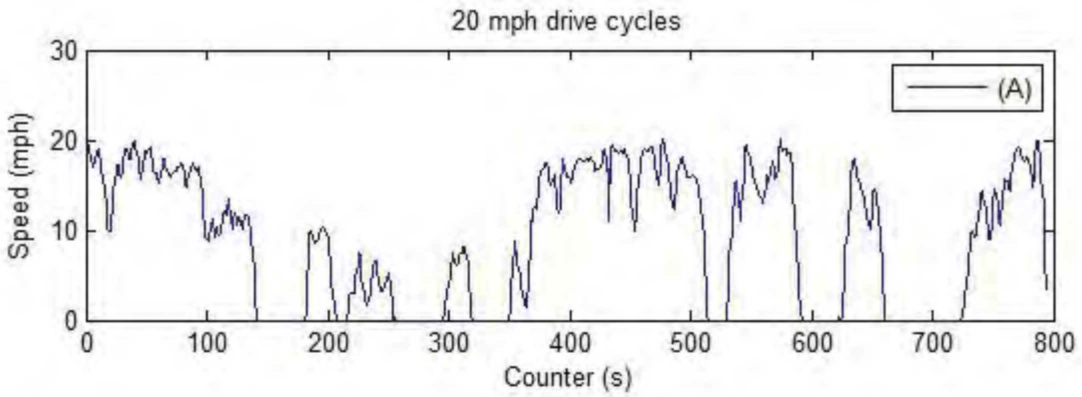
Furthermore, on non-residential street segments, the average proportion of data points in excess of 20mph rarely exceeds 50%. Once again, speed limit does not appear to be the determining factor of driving style and vehicle behavior.

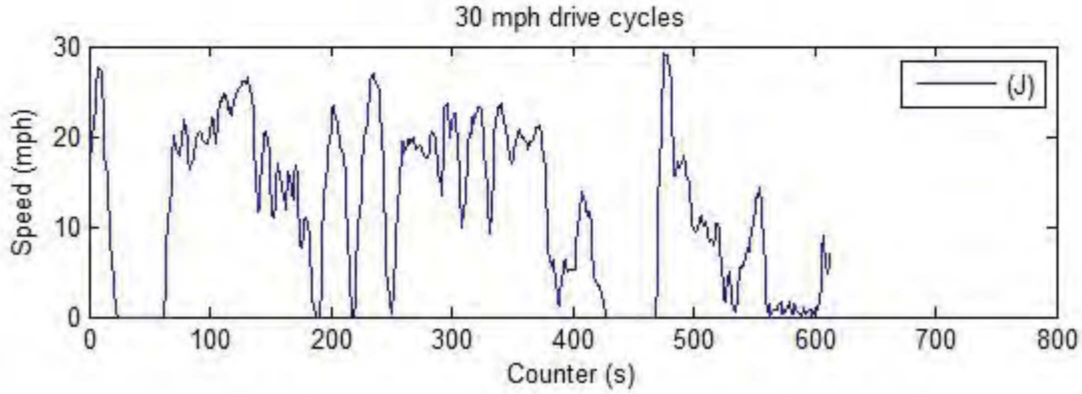
SUMMARY

- A greater range of speeds are observed on 30mph route segments compared to 20mph route segments
- A larger proportion of time was spent accelerating and decelerating on 30mph route segments
- Average speeds are higher on 30mph route segments – when restricted to cruise operating mode only, a statistical significant difference was seen
- Time of day was not seen to have a large effect on this dataset
- No relationship between average speed and speed limit was seen on residential streets
- On non-residential streets, in most cases (6 out of 8 segments), the proportion of observed speeds over 20mph was less than 40%

ESTIMATION OF TAILPIPE EMISSIONS

In order to understand the impact of any changes in driving style on tailpipe emissions, a series of drive cycles were developed for both 20mph and 30mph roads. These drive cycles were generated using a random stratified sampling technique. In total, eight drive cycles were generated for 20mph roads and eight for 30mph roads. All were approximately 3.2km in length, but had different speed and acceleration characteristics. Examples of each are shown below:





Rather than a standard average speed method, an instantaneous emission model was used to generate estimates of pollutant emissions for each drive cycle. The model, AIRE, uses the dynamic characteristic of the vehicle alongside other parameters such as fuel type and engine size. These emission estimates were then normalized by drive cycle length to give an emission factor (pollutant mass per unit distance).

Vehicle type	Drive cycle speed limit	NO_X (g/km)	PM_{10} (g/km)	CO_2 (g/km)
PETROL 1.4 – 2.0 litre, EURO IV	20	0.0726	0.00218	271.95
PETROL 1.4 – 2.0 litre, EURO IV	30	0.0673	0.00237	266.35
Impact of 20mph drive cycle		+7.9%	-8.3%	+2.1%
DIESEL 1.4 – 2.0 litre, EURO IV	20	0.7437	0.01758	201.58
DIESEL 1.4 – 2.0 litre, EURO IV	30	0.8104	0.01917	203.48
Impact of 20mph drive cycle		-8.2%	-8.3%	-0.9%

Emissions of NO_X and CO_2 are seen to be higher over 20mph drive cycles for petrol cars and generally lower for diesel cars. PM_{10} emissions improve for smaller vehicles over 20mph drive cycles (less than 2.0 litre engine size), but are shown to increase for larger vehicles. The order of magnitude is such that future trends in fleet composition will be important.

The modelling methodology was validated by the use of tailpipe emissions collected with a high-resolution portable emissions measurement system (PEMS). The data was provided by Emissions Analytics, a private company who assess on-road emissions and fuel consumption. Real-world measurements were compared to modeled estimates from AIRE, and seen to be in general agreement for trend.

SUMMARY

- A random stratified sampling method was used to generate 16 drive cycles (8 for 20mph, 8 for 30mph roads) from previously defined route segments

- The AIRE model was used to estimate emissions of NO_X, PM_{10} and CO_2 for each drive cycle; these were then normalised to give emissions factors (pollutant mass per unit distance)

- NO_X emission factors are higher for petrol vehicles over 20mph drive cycles compared to 30mph drive cycles; for diesel vehicles they are lower

- Given the higher contribution of diesel vehicles to emissions of NO_X, this is a significant result

- PM_{10} emission factors are lower for both petrol and diesel vehicles over 20mph drive cycles compared to 30mph drive cycles; the exception is vehicles with engines over 2.0 litres in size

- CO_2 emission factors follow the same pattern as NO_X, although with smaller percentage changes, demonstrating increased fuel consumption when travelling at lower speeds

- It is concluded that it would be incorrect to assume a 20mph speed restriction would be detrimental to ambient local air quality, as the effects on vehicle emissions are mixed

- The short-comings of using average speed models is highlighted, with the specific example of the potential to underestimate emissions of NOX from diesel passenger cars

- It is noted that this analysis is only relevant to per vehicle emissions, and does not account for potential associated impacts of a speed restriction, such as congestion

SPEED CONTROL METHODS

In order to assess the impact of different speed control methods, comparison was made between route segments with particular characteristics. Ten segments were chosen that exhibited a range of speed control characteristics at both 20mph and 30mph. Emission factors were estimated as previously for a range of observations. Lower emission rates were seen on route segments where it would be expected that speed can be better maintained. However, the ability of a vehicle to maintain an average speed was found to be dependent not only on methods of speed control, but also of traffic management features such as pedestrian crossings and signalised junctions.

BRAKE AND TYRE WEAR

Changes in brake and tyre wear are linked to the demand for power of the vehicle. At lower speed limits, it is expected that changes in average speed and accelerating and decelerating behaviours will reduce transient demand for power. This in turn is expected to be beneficial to non-tailpipe emissions of particular matter. This is identified as an area where knowledge of modeling emissions, particularly on a second-by-second basis, is lacking and further research is required.

PROJECT FINDINGS

It is concluded that it would be incorrect to assume a 20mph speed restriction would be detrimental to ambient local air quality, as the effects on vehicle emissions are mixed

Driving styles (as characterised by the vehicle operating mode and distribution of cruise speeds) are different on 20mph roads as compared to 30mph roads. This was achieved by splitting the measured vehicle trajectories into segments based on speed limit and further aggregating the data. Whilst time of day and day of the week was not seen to be particular importance, site-specific analysis showed the variation in recorded vehicle behaviour at and between sites. In particular, residential streets with 30mph speed limits were often shown to have vehicle speed not exceeding 20mph. This suggests imposition of a 20mph speed restriction will not impact the majority of vehicle behavior. This was also true of heavily trafficked non-residential streets.

London-specific 20mph and 30mph drive cycles for use with instantaneous emissions databases were developed using a random stratified sampling technique. The effects of a 20mph speed restriction on were shown to be mixed, with particular benefit seen for emissions of particulate matter and for diesel vehicles. The methodology was validated by consideration of real-world tailpipe emissions test data. It was therefore concluded that air quality is unlikely to be made worse as a result of 20mph speed limits on streets in London. This analysis is suitable for per-vehicle emission rates, and does not consider secondary effects such as congestion.

Route segments where traffic flow was more likely to be interrupted were shown to have higher emission rates. However, this could not always be attributed to traffic calming measures (particularly vertical deflection) and was often the result of other traffic management infrastructure (pedestrian facilities and junctions). In general it is accepted that the lower demand for power at lower speed limits (with fewer) acceleration events) is likely to be beneficial to particulate matter emissions associated with brake and tyre wear.

Differences between the predicted emission factors for NO_x from standard average-speed emission methods and those developed in this study were minor for the case of light-duty petrol vehicles. However, differences for light-duty diesel vehicles were large, suggesting that standard methods may substantially underestimate the contribution of these vehicle classes to NO_x emissions in congested urban areas. Heavy-duty vehicles were not considered here, but should be investigated in future research. There is great potential for further work in this area. Although the modeling work here has been validated, application of high-resolution portable emissions measurement systems to specific cases in London would yield useful data that could better help answer these research questions. A particular deficiency in current understanding is around tyre and brake wear. These are a significant, and increasing, proportion of particulate matter is urban areas, and better knowledge of the influences on their emission will further inform traffic management and control decisions.

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GLOSSARY

CO_2	Carbon dioxide
DEFRA	Department for Environment, Food and Rural Affairs
DfT	Department for Transport
Drive cycle	A specific speed trace used for testing vehicle performance
ECE	Economic Commission for Europe
EUDC	Extra Urban Driving Cycle
Horizontal deflection	Any traffic calming measure which reduces the horizontal alignment of the link over a short distance
MATLAB	Technical computing language particularly suitable for numerical analysis and algorithm development
NAEI	National Atmospheric Emissions Inventory (UK)
NO_X	Oxides of nitrogen
PM_{10}	Particular matter between 2.5 and 10 microns
TfL	Transport for London
TRL	Transport Research Laboratory (TRL Ltd)
Speed trace	A representation of vehicle speed over time
Vertical deflection	Any traffic calming measure which increased the vertical alignment of the link over a short distance

1 BACKGROUND

1.1 SCOPE OF PROJECT

This report details a research project undertaken in the first quarter of 2013, designed to assess the potential impact of introducing 20mph zones in central London. This includes the expected impact of the changes in driving styles, levels of emissions, different methods of speed control and brake and tyre wear. Current estimates of vehicle producing additional NO_X at the lower speed limit is based on average speed models, and may therefore not be appropriate. As such, the central London authorities (as represented by the City of London) requested an assessment of the expected impact of 20mph speed restrictions [1].

This work has been carried out by the Transport and Environmental Analysis Group, Centre for Transport Studies, Imperial College London [2].

1.2 PROJECT OBJECTIVES

The project will seek to understand [1]:

1. The difference in driving styles between 20mph and 30mph roads
2. The impact of this change on estimated tailpipe emissions of NO_X, PM_{10} and CO_2
3. The impact on emissions of different methods of speed control on urban roads
4. The impact on emissions from brake and tyre wear of a 20mph zone

2 CURRENT UNDERSTANDING

2.1 EXISTING PRACTICE

In recent years there has been an increasing trend towards the implementation of 20mph zones in urban areas. In general, the permissible speed limit on local roads is determined by the local authority. The method of speed calming is also determined by the local transport authority[1], with guidance available from the DfT [3].

The DfT [4] has also set out some guiding principles for making decisions regarding the determination of local speed limits:

- Accident history
- Road geometry
- Presence of vulnerable road users
- Road function
- Existing traffic speeds
- Road environment

The last category includes the possible impacts of the scheme, including on air quality. This is particularly important in urban areas, with increasing attention towards air pollution and public health [e.g. 5]. Consequently there is a need to understand the impacts of different urban speed limits on driving style and vehicle emissions.

Traditionally, average speed models[2] have been applied to scheme assessment. These are generally based on a particular type of vehicle and a general type of driving (urban, motorway, rural) [6]. This aggregate approach is difficult to apply to local traffic management schemes, as it does not distinguish between different traffic management scenarios that achieve the same average speed.

2.2 PREVIOUS RESEARCH

There has been much research into the impacts of various traffic management methods, including speed calming, on vehicle emissions and air quality. In general, it is accepted that methods to smooth traffic flow will reduce vehicle emissions and the associated air pollution [e.g. 7]. Conversely, increasing the number of stops (and starts) is likely to worsen the problem. This is expanded upon in later sections.

Previous research [8] has also demonstrated that speed calming methods which interrupt the steady-flow of traffic tend to increase emissions. Conversely, research into air quality of speed-restriction zones [9] has found a reduction in pollutant concentrations associated with speed reduction. In all cases, research has been site specific.

Whilst building on previous research and understanding, this project is designed to be specific to the types of roads and speed calming methods seen in central London.

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[1] For example: in London local authorities are allowed to construct speed humps on any road

[2] Such as the NAEI (National Atmospheric Emissions Inventory)

3 DATA COLLECTION

The main data for the analyses described in this report are from empirical data collection across London in January and February 2013.

3.1 METHODOLOGY

Vehicle trajectories were recorded through the use of a u-blox ANTARIS GPS module [10]. Data regarding time, speed and position were recorded at a frequency of 1Hz. In addition, information regarding the precision[3] of the GPS signal was logged for further analysis.

Several routes were designed in order to cover a range of different traffic conditions as required (as per section 1.2). These routes were repeated to provide multiple observations (laps).

Photograph 1 (L-R): logging setup; antenna position; GPS module

In the course of experimental design, particular variables were identified as having the potential to impact on the measured driving styles (and consequently estimated emissions) – these were controlled where possible (table 1).

Table 1: Variables considered during experimental design

Variable	Method of control
Type of road	Independent variable; control not necessary
Vehicle	The same model of vehicle was used throughout
Driver	The same driver was used throughout
Other traffic	Multiple observations collected to reduce the impact of particular incidents
Weather conditions	All data collected in a short time-window and observations made

[3] PDOP (positional dilution of precision) is a measure of accuracy of 3D position, based on the geometry of available satellites

The driver had knowledge of all routes and was familiar with driving in central London. Although an ideal data set would cover a range of different driver and vehicle types, this was not feasible in within the scope of this project. As such a decision was made to control as much as possible and collect data for what was deemed a “typical” situation in London.

3.2 SITE SELECTION

Six routes were chosen against a range of criteria. In particular, it was important to cover a suitable range of different road types and locations such that results would be applicable to central London as a whole. Before final selection, a pilot data collection study was carried out. In several cases the final route was amended on the basis of this study. A summary of these routes is shown in table 2, with more details contained within the appendices of this report.

Table 2: Selected routes for data collection

Route	Length (miles)	Borough	Streets (abridged)
A	2.0	City of London	London Wall, Houndsditch, Aldgate, High Street, Bishopsgate, Threadneedle Street, Gresham Street
B	2.1	Islington	Liverpool Road, Holloway Road, Upper Street, Cross Street, Essex Road, Islington Park Street
C	2.3	Camden	Camden High Street, Kentish Town Road, St Pancras Way, Royal College Street, Camden Street
D	2.0	Southwark / Lambeth	The Cut, Baylis Road, Westminster Bridge Road, Borough Road Marshalsea Road, Union Street
E	2.4	Westminster	Vauxhall Bridge Road, John Islip Street, Horseferry Road, Buckingham Gate
F	2.7	Kensington & Chelsea / Westminster	Exhibition Road, Queen’s Gate, Onslow Gardens, Old Church Street

Figures 1 – 6 show each route in map form (direction of travel is not shown; please refer to detail in the appendices).

Figure 1: Route A – City of London (map data © Google)

Figure 2: Route B – Islington (map data © Google)

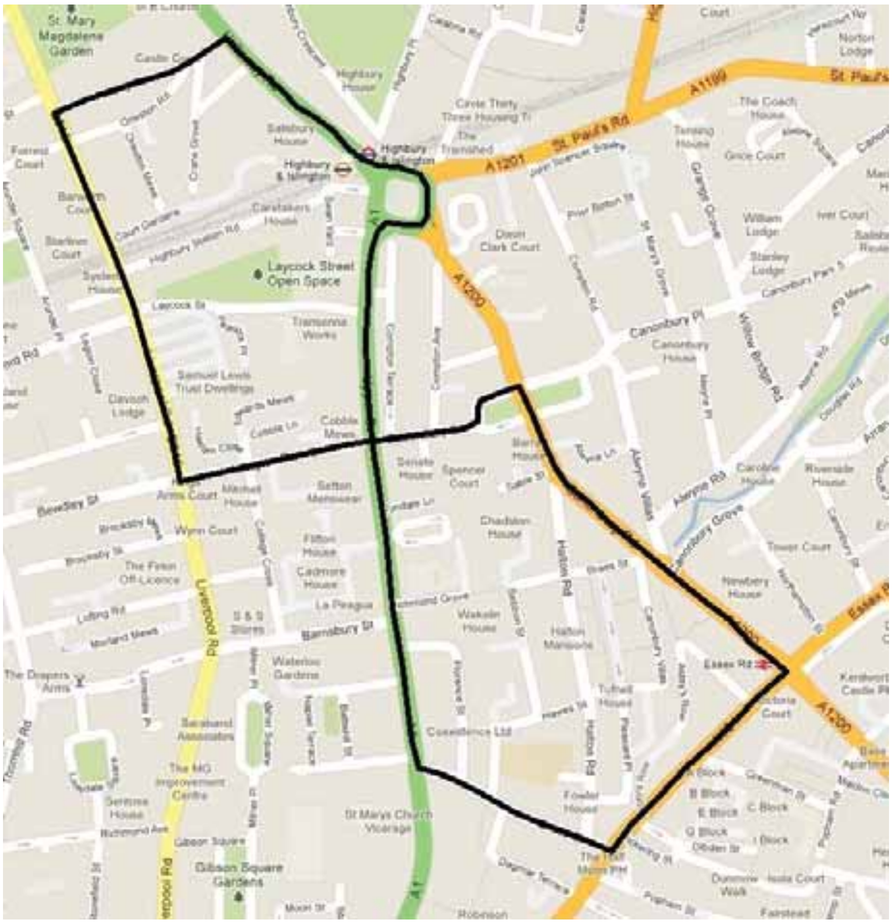


Figure 3: Route C – Camden (map data © Google)

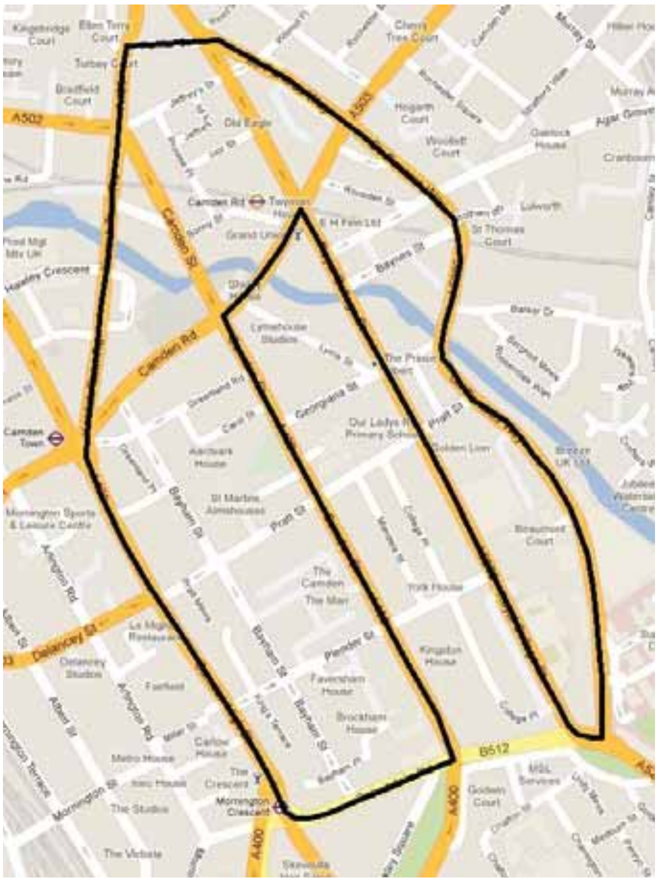


Figure 4: Route D – Southwark / Lambeth (map data © Google)

Figure 5: Route E – Westminster (map data © Google)

Figure 6: Route F – Kensington & Chelsea / Westminster (map data © Google)

3.3 DATA CLEANING AND PROCESSING

Eight days were spent collecting data, wholly contained within the period 29/01/2013 to 20/02/2013. This covered a range of different days of the week (Monday, Tuesday, Wednesday, Thursday, Saturday) and times of day (approximately between 10am and 8pm).

Initial processing involves splitting log files into individual laps and checking the integrity of the data. A geographic bounding box was defined for the start and end of each route to allow splitting. Concurrently, areas of poor positioning precision[4] were identified and omitted. Figure 7 shows an example of the data before and after lap processing.

Figure 7: Vehicle trajectory data before and after processing (route F) (map data © Google)

[4] Mainly due to systematic problems with achieving a GPS fix (for example, due to the presence of an under-pass)

3.4 DATA SUMMARY

Filtering and initial processing led to around 22 hours of data to be taken forward to the analysis stage. This was spread over six routes and several different times of day[5]. This is summarised in table 3.

Table 3: Summary of collected data

Route	Days	Observations	Times of day	Total time (mins)
A	2	14	Inter-peak PM peak	235
B	3	18	Inter-peak Weekend	240
C	2	15	Inter-peak PM peak	205
D	2	14	Inter-peak PM peak	170
E	3	27	Inter-peak PM peak Weekend	280
F	2	12	Inter-peak PM peak	195

"Observations" refers to the number of completed laps on each route

[5] In this case, inter-peak refers to data collected between 10am and 4pm, PM peak refers to data collected after 4pm

4 DRIVING STYLES ON 20MPH ROADS

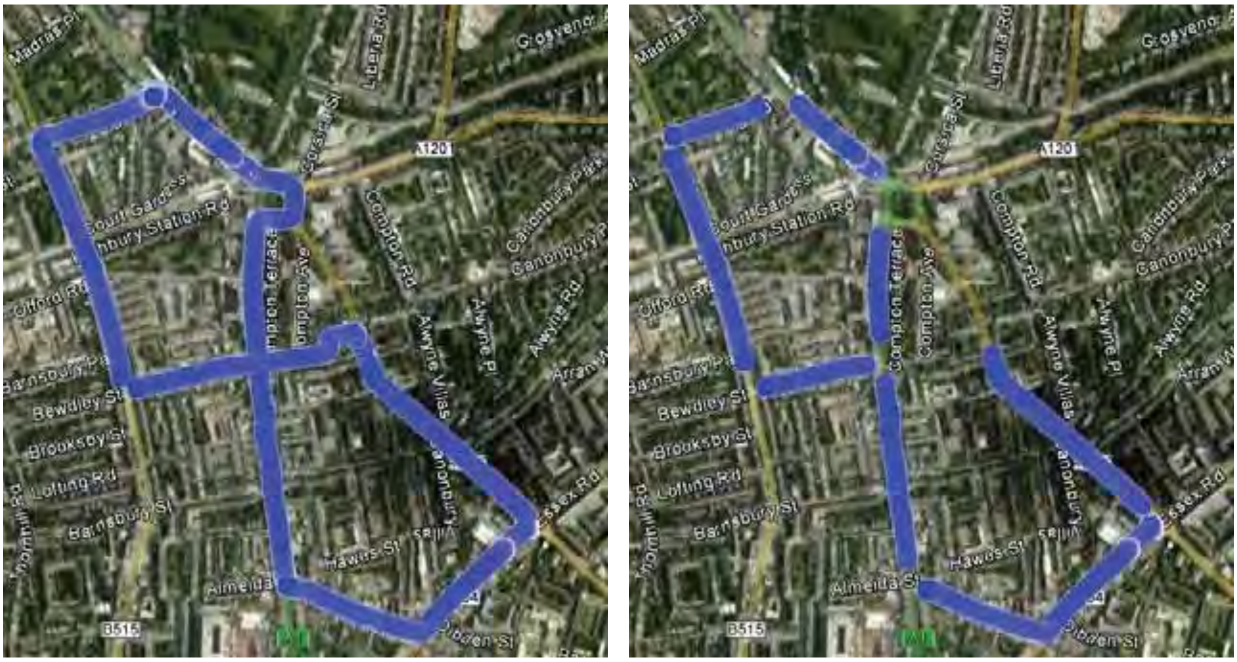
Objective 1 (section 1.2) is related to understanding differences between driving style and vehicle behaviour on 20mph roads compared to the 30mph roads (standard in urban areas).

4.1 DATA POST-PROCESSING

The data collection sites (section 3.2) contain a range of different traffic conditions. In order to assign the correct link with the appropriate speed limit, the routes are first split into segments. Each segment is characterised by one or more bounding boxes which define the upper and lower limits of longitude and latitude. In addition to dividing by speed limit, it was also thought necessary to remove the influence of major junctions. Existing research (section 2.2) has shown that junctions can have significant influence on vehicle speeds and emissions. As the junction configuration and timing is somewhat independent of the mandated speed limit, these were removed from the data to avoid unduly influencing results.

A MATLAB algorithm is used to split each lap into the constituent segments. An example of the segmentation is shown in figure 8. The signalized roundabout at the junction of Holloway Road and Upper Street (A1) can be seen to have been removed to avoid skewing the data.

Figure 8: Example of segment splitting (route B) (map data © Google)



In total, 38 segments are defined. These are summarised in table 4. It is important to remember that these are defined by link characteristic, and not length, and so the number of segments is not necessarily an indicator of the amount of data.

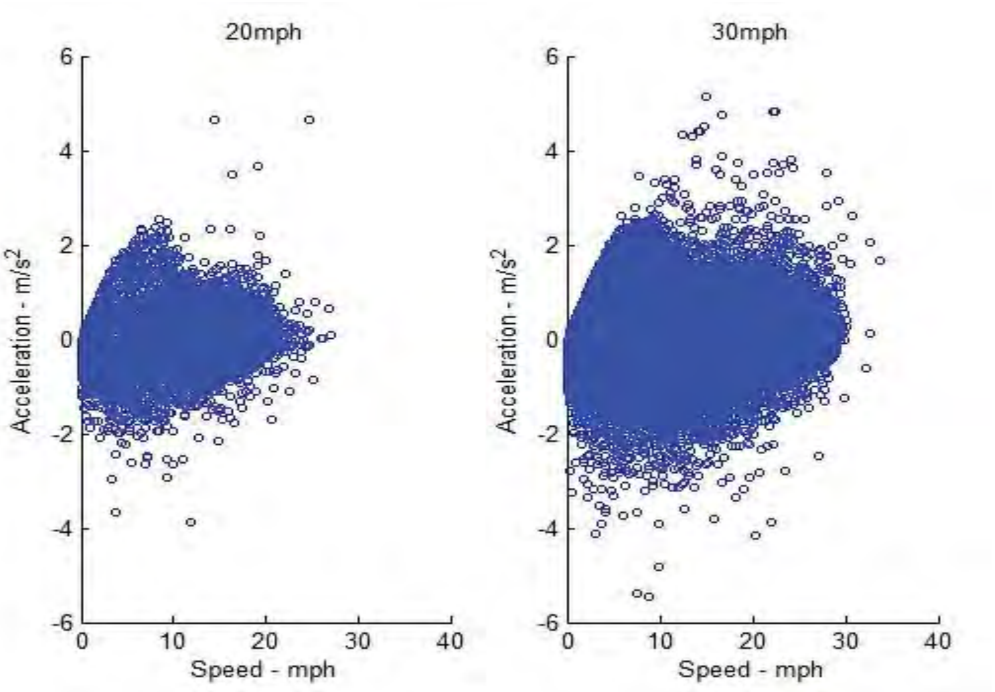
Table 4: Summary of route segments

Route	Number of segments	Number of 20mph segments	Number of 30mph segments
A	6	0	6
B	9	5	4
C	7	2	5
D	7	2	5
E	4	0	4
F	5	1	4
Total	**38**	**10**	**28**

4.2 SUMMARY STATISTICS

The range of data collected on each road type can be seen in plots of speed and acceleration[6] (figure 9). The acceleration phase of operation is particularly important for vehicle emissions due to the additional demand for power (see section 4.2.1).

Figure 9: Data range by road type (speed and acceleration)



[6] Including negative acceleration (deceleration)

4.2.1 VEHICLE OPERATING MODE

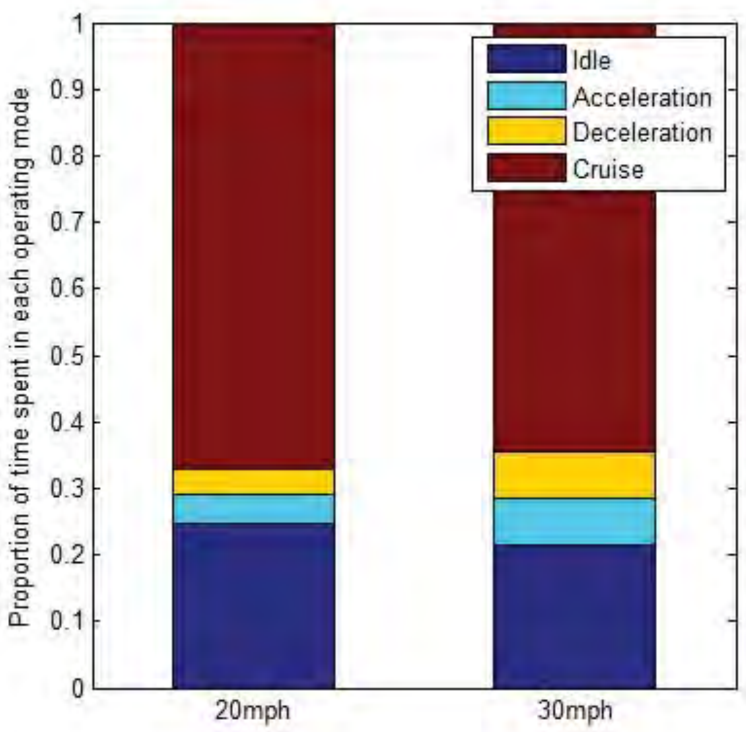
Frey et al [11] discuss the statistical significance associated with different average emissions rates for pollutants by vehicle operating mode. This is a simplified method of describing the dynamic characteristics of the vehicle at any given time (table 5). The data collected were separated into vehicle operating mode for further analysis.

Table 5: Vehicle operating mode definition [11]

Mode	General definition	Criteria applied
Idle	Zero speed, zero acceleration	Speed = 0
Acceleration	Non-zero speed, positive acceleration	Speed > 0 Acceleration[7] > 0.9 m/s^2
Deceleration	Non-zero speed, negative acceleration	Speed > 0 Acceleration < -0.9 m/s^2
Cruise	Non-zero speed, zero acceleration	All other conditions

For these data, the majority of time is spent in the cruise mode of operation (figure 10), with marked differences in time spent accelerating and decelerating between categories of road. This could be a facet of post-processing and study design rather than a characteristic the type of road.

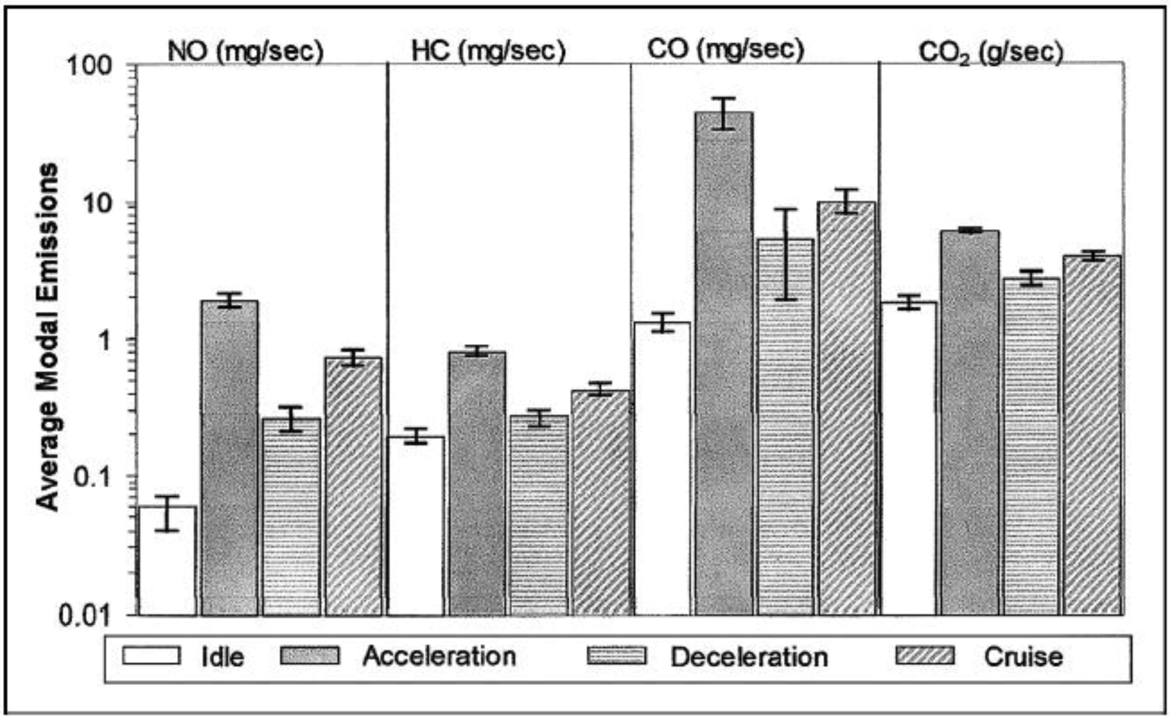
Figure 10: Vehicle operating mode by road type



[7] $0.9m/s^2$ is approximately 2mph/s

This has implications for the emission induced by both different speed limits and different forms of speed control. The acceleration mode of operation requires additional power to overcome the resistive forces acting against a vehicle. Therefore, pollutant emission rates (mass per unit time) are higher when the vehicle is accelerating. An example is shown in figure 11.

Figure 11: Example average modal emission rates [from 11]

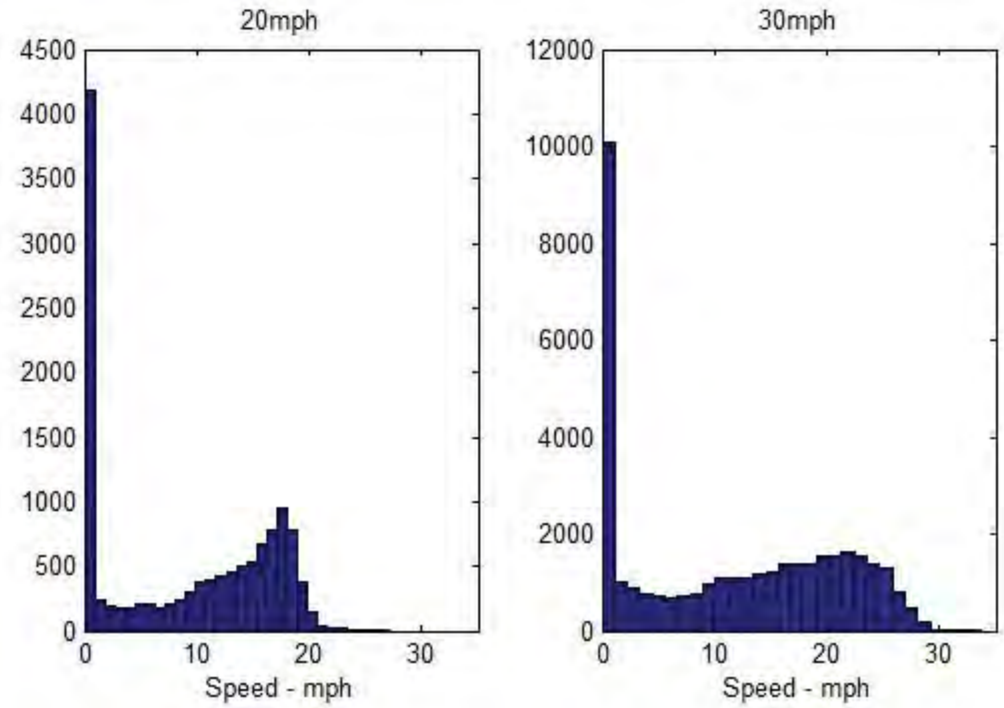


This leads to a general rule, allowing hypothesis to be formed around the potential impact of various traffic management measures; smoother traffic flows reduce vehicle emission rates.

4.2.2 DISTRIBUTION OF VEHICLE SPEEDS

Histograms of vehicle speed (figure 12) show similarly shaped distributions for both types of road. The distribution for 30mph roads appears slightly flatter for speeds over 10mph, reflecting the greater range of data.

Figure 12: Histograms of vehicle speed by road type



Once again it is possible that differences seen are a result of how the data has been segmented rather than a particular characteristic of aggregate road type. For example, a high proportion of time spent accelerating and decelerating (table 6) could be explained by a greater number of signalised intersections or the presence of pedestrian crossings within the segments selected.

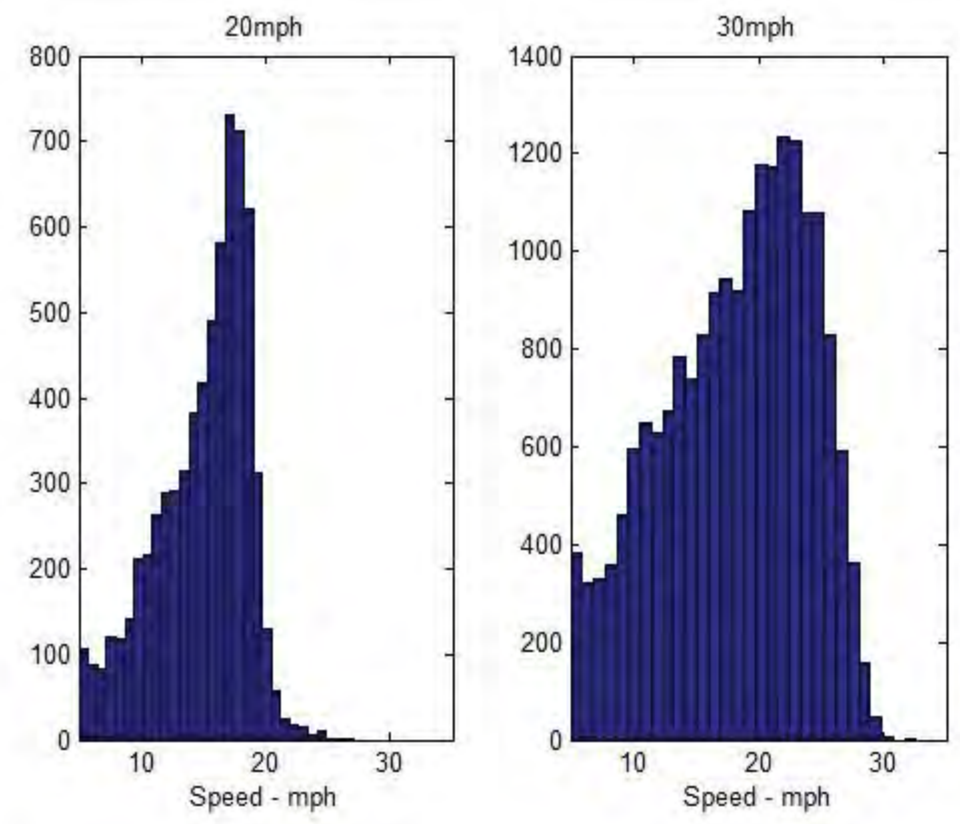
Table 6: Proportion of time spent accelerating/decelerating by road type

	20mph	30mph
Total time (s)	11,485	35,802
Proportion of time accelerating (%)	4.4%	3.7%
Proportion of time decelerating (%)	7.1%	6.8%

Whilst this is an important part of vehicle operation (particularly when considering emissions), some sort of normalisation must be undertaken so as to compare between the different road types.

To address this, the data is limited to include only the “cruise” mode of vehicle operation[8] (figure 7). This would be expected to not only remove the influence of many junctions and signalised crossings, but potentially also of traffic calming measures (such as vertical deflection in the form of speed humps). It is recognised that certain methods of speed control induce acceleration and deceleration. As such, this will be investigated in section 6.

Figure 13: Histogram of vehicle speed (limited to cruise only)



Speeds appear on average lower in 20mph segments. Consideration of descriptive statistics supports this, with mean and median cruise speeds lower in 20mph zones. There also appears to be less variability, as displayed by the lower standard deviation (table 7).

Table 7: Summary statistics (cruise mode of operation only)

Cruise only	**20mph**	**30mph**
Mean speed (mph)	14.9	18.2
Median speed (mph)	15.8	19.0
Standard deviation (mph)	3.7	5.8

In order to test that the difference in average cruise speed between types of road is statistically significant, a suitable test must be chosen. Histograms of the data do not suggest the data follows

[8] A slightly altered definition In order to capture more “steady state” driving conditions, where vehicle speed is greater than 5mph, and vehicle acceleration is between -0.9 and +0.9 m/s^2

a normal distribution, as the distributions are highly negatively skewed. This is confirmed by q-q plots of the data and computation of the skewness statistic.

Since the data is not normally distributed, a non-parametric hypothesis test is required. The Mann-Whitney *U* test allows comparison between these different categories.

H_0: *data from categories x and y are taken from continuous distributions with equal medians*
H_1: *data are not from continuous distributions with equal medians*

On application of this test, the null hypothesis was **rejected**, and we therefore conclude that the data were drawn from different distributions characterised by different medians. In practical terms, the conditions observed on the two categories of road are different in so far as they result in statistically different speeds.

4.3 TIME OF DAY ANALYSIS

Variations in traffic conditions during time of day and time of week have the potential to impact average speeds and journey times. This in turn will alter the potential impact of 20mph zones on vehicle emissions and air quality.

Table 8: Average lap time by time period

Time of day	Average time (s, all laps, all segments)	
	Route B (Islington)	Route E (Westminster)
Inter-peak	523	376
PM peak	-	342
Weekend (Saturday)	540	340

Estimates of average traffic speeds [12] demonstrate the difference based on time of day (table 9). Detailed weekend data are not available, although cordon surveys suggest whilst the amount of general traffic is around 20% lower in central London [13], fleet mix is weighted more heavily in favour of passenger cars rather than goods vehicles.

Table 9: London traffic average speed [5]

Time of day	Average speed (mph, 2011 data)	
	Inner London[9]	Central London[10]
Inter-peak	21.4	13.6
PM peak	18.4	13.8

[9] Routes chosen for this study considered "Inner London" are route B (Islington) and route C (Camden)
[10] Routes chosen for this study considered "Central London" are route A (City of London), route D (Southwark / Lambeth), route E (Westminster) and route F (Kensington & Chelsea / Westminster)

Variation in lap times of the collected data does not appear particularly large (figures 14 and 15). As such, it is concluded that time of day should not be a factor in future analyses.

Figure 14: Time to complete lap (route E)

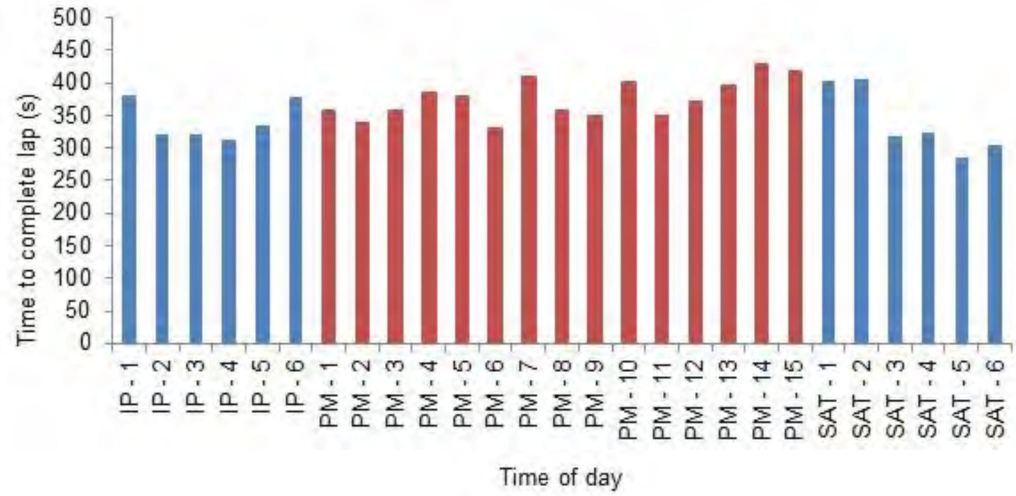
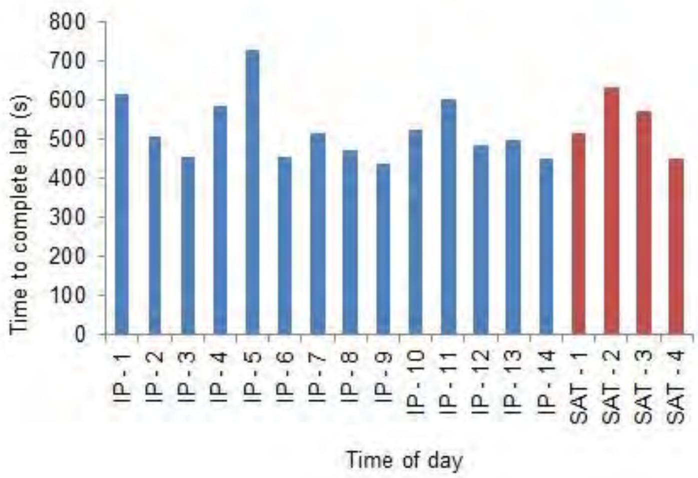


Figure 15: Time to complete lap (route B)



4.4 SITE SPECIFIC ANALYSIS

Post-processing (described in section 4.1) split the data into 38 segments. These segments are characterised by certain features, such as the speed limit, the presence of traffic calming infrastructure, and the general type of street. The potential for comparison between segments, also incorporating time of day, is large. For simplicity (and since not all comparisons are appropriate), several interesting combinations have been selected.

4.4.1 RESIDENTIAL STREETS

Several streets have been identified as "residential". These have a range of different operating conditions, but are all considered to be streets where housing predominates. The segments are described in table 10 – route A does not feature as it does not contain any residential sections.

Table 10: Residential streets for comparison

Segment	Route	Speed limit (mph)	Length (m)	Description
Liverpool Road	B	20	390	Wide residential with speed cushions and zebra crossings
Royal College Street	C	20	380	Wide one-way residential with speed cushions
Baylis Road	D	30	270	Wide residential, some traffic islands and good cycle provision
Marshalsea Road	D	20	230	Zebra crossing, but no calming and a more important through route
Union Street	D	20	460	Narrow residential, one-way in parts with speed cushions
John Islip Street	E	30	540	Residential street with speed cushions and much on-street parking
Onslow Gardens	F	30	280	Residential street with on-street parking
Old Church Street	F	30	340	Residential street with on-street parking

Although it is not thought that time of day is a significant explanatory within this data set, a filter was initially added to distinguish between inter-peak (IP) and PM peak (PM) times[11]. However, to allow for a robust analysis, observations were aggregated so that n was greater than 10 in each category.

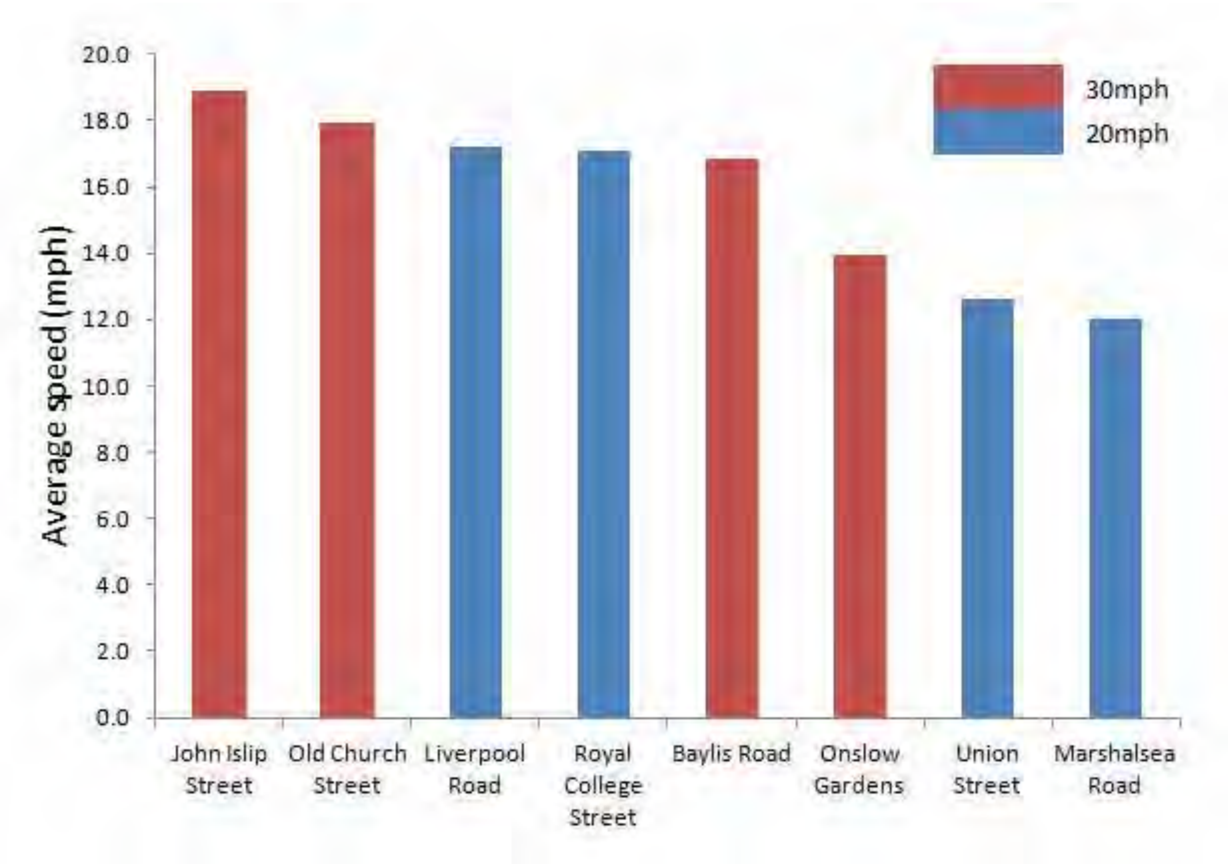
[11] The data is limited to week days only

Table 11: Summary statistics for each residential route segment (ordered by average speed)

Segment	Route	Observations (number of laps)	Speed limit (mph)	Average speed[12] (mph)	Standard deviation[13] (mph)
John Islip Street	E	21	30	18.9	6.2
Old Church Street	F	11	30	17.9	9.2
Liverpool Road	B	14	20	17.2	1.6
Royal College Street	C	15	20	17.1	3.1
Baylis Road	D	14	30	16.8	8.8
Onslow Gardens	F	12	30	13.9	7.2
Union Street	D	14	20	12.6	6.0
Marshalsea Road	D	14	20	12.0	7.8

From these data (table 11), there does not appear to be any systematic relationship between speed limit and the measured speeds on the residential streets. This is illustrated in figure 16.

Figure 16: Average speed (mph) on residential streets



Of particular interest are the average speeds and operating conditions of the streets with a stated speed limit of 30mph (table 12).

[12] Average speed is calculated per observation, and then averaged across all observations
[13] Standard deviation applies to the entire data set

Table 12: Operating conditions of 30mph residential streets (ordered by proportion >20mph)

Segment	Route	Average speed (mph)	Speed limit (mph)	Average proportion idle (%)	Average proportion[14] >20mph (%)
Old Church Street	F	17.9	30	7.7%	57.2%
Baylis Road	D	16.8	30	8.1%	49.9%
John Islip Street	E	18.9	30	0.0%	47.9%
Onslow Gardens	F	13.9	30	4.7%	19.5%

Consideration of the proportion of time spent at speeds in excess of 20mph highlights the importance of considering other metrics aside from average speed. Variable conditions experienced on each link can be further investigated by plotting time series of speed. These show how vehicle speed varies with time and therefore indicates the time spend accelerating, decelerating and idle. In all cases, the trace covers the segment only. As such, a shorter trace indicates that the segment was completed more quickly.

Figures 17, 18, 19 and 20 show separate observations for Baylis Road, John Islip Street, Onslow Gardens and Old Church Street respectively. When viewed in conjunction with the notes made during data collection, the reasons for different results become clearer.

For example

- Baylis Road (ii) (figure 17): remarks were made regarding a longer queue when approaching the western set of traffic lights. This is consistent with the speed trace (from 20 seconds onwards)
- Onslow Gardens (figure 19): the influence of a queue at the southern set of traffic lights (i) and no queue (ii)
- Old Church Street (figure 20): the influence of delay at a preceding junction (i) can be seen by the acceleration at the start the link

Given the results of this, any estimation of emission from a particular link must not only include multiple locations, but also incorporate multiple runs to capture the potential variation in traffic conditions.

[14] Calculated for each observation and then averaged across all (un-weighted)

Figure 17: Baylis Road vehicle speed trace

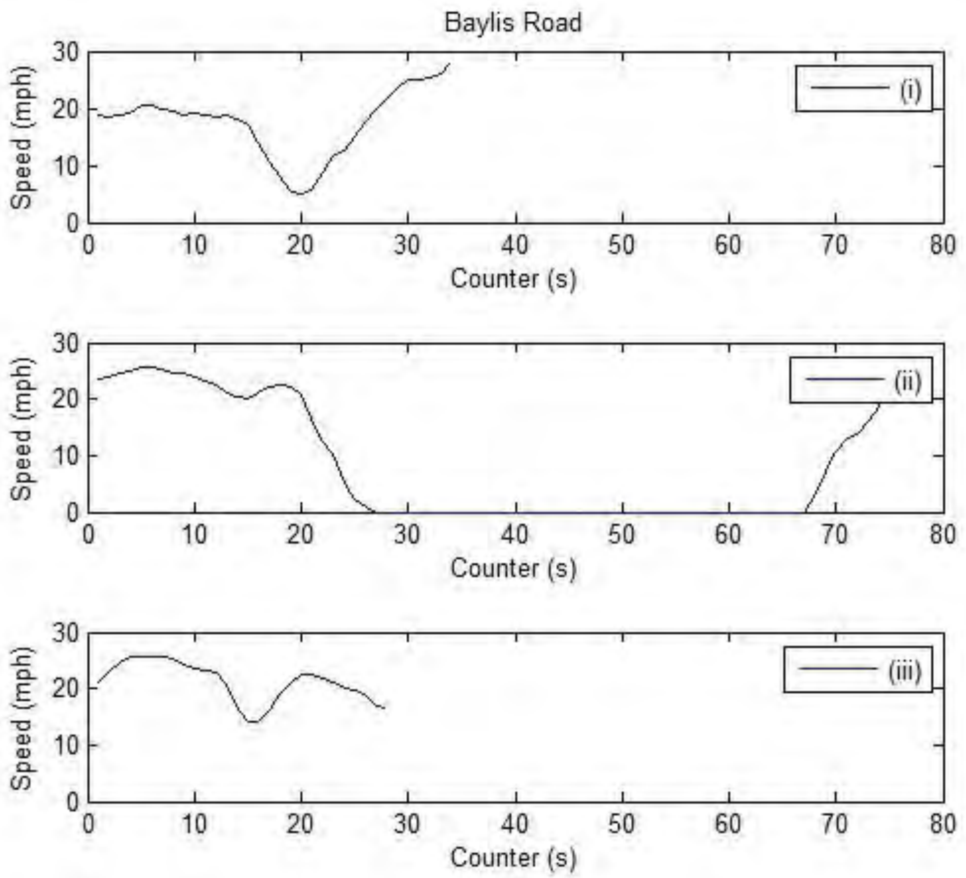


Figure 18: John Islip Street vehicle speed trace

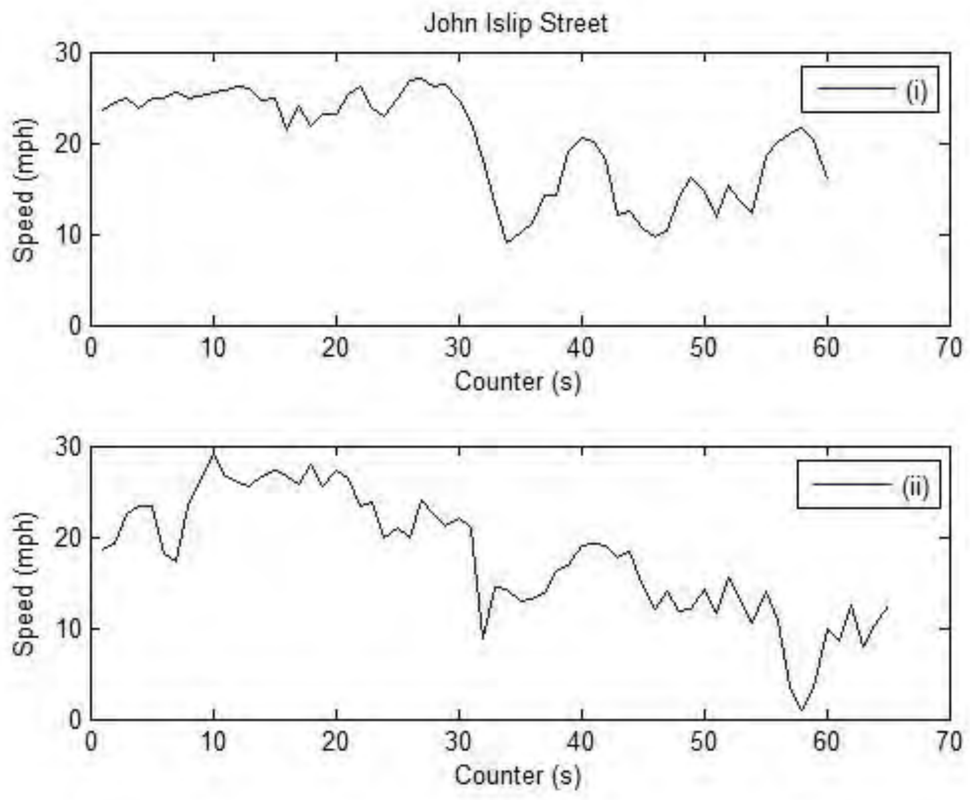


Figure 19: Onslow Gardens vehicle speed trace

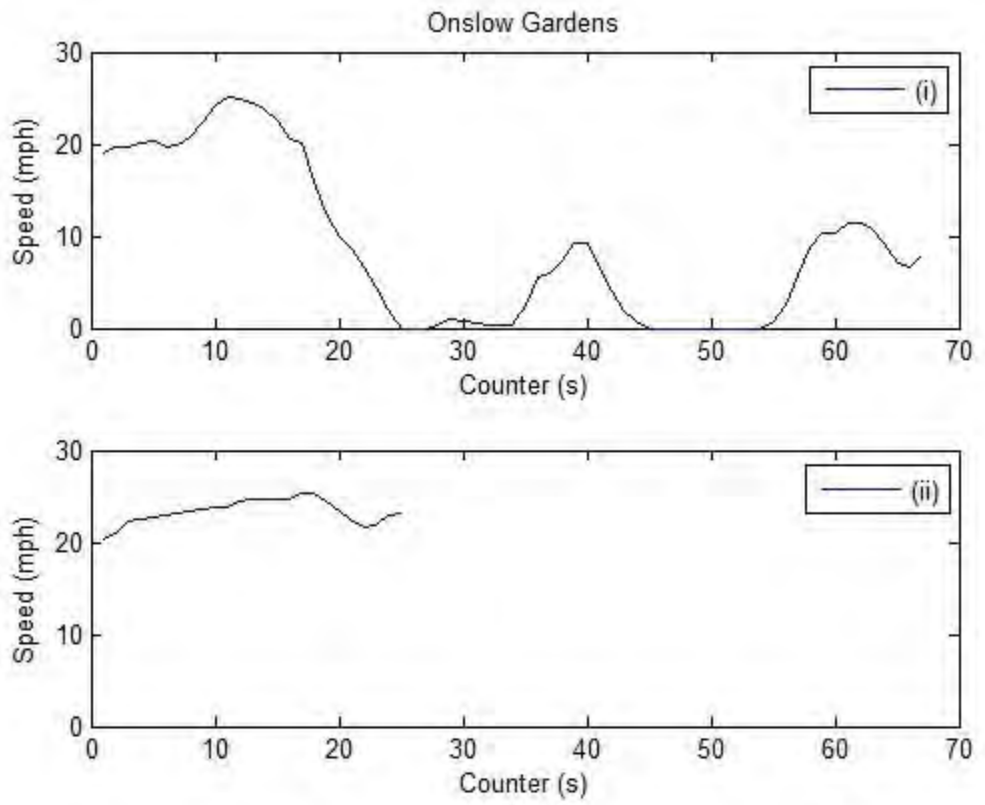
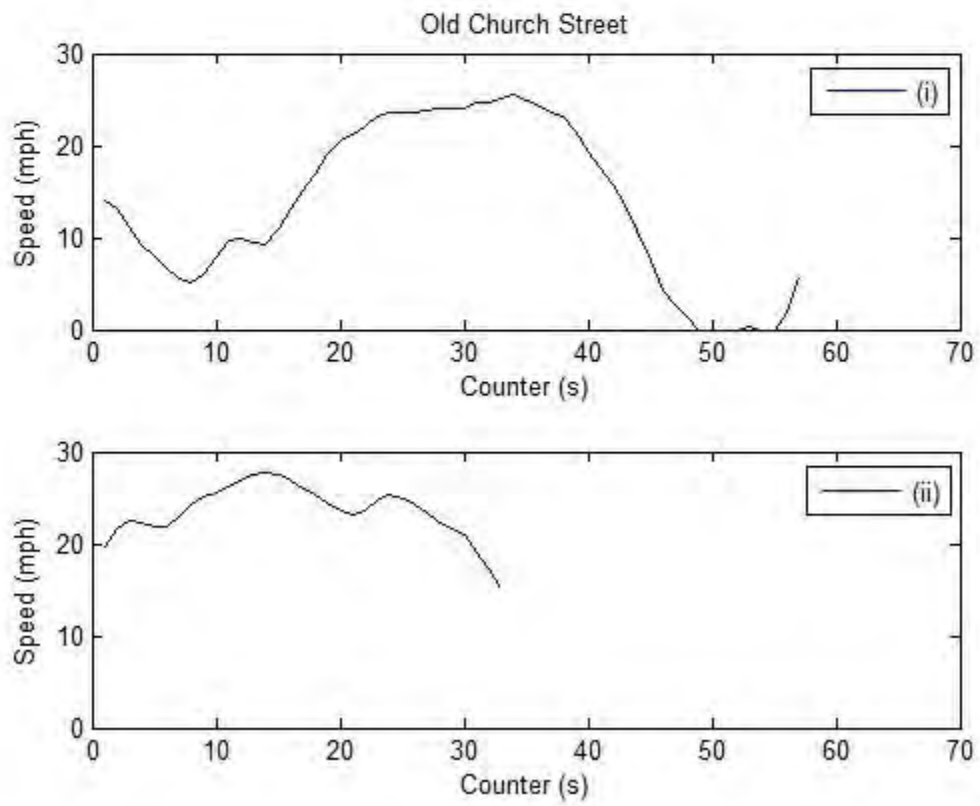


Figure 20: Old Church Street vehicle speed trace



4.4.2 NON-RESIDENTIAL STREETS

Similarly, several types of non-residential streets have been identified for comparison (table 13). Some may be characterised as being more "high street" in nature (for example, with shop frontage rather than housing) with greater pedestrian activity. Others are more important urban links. All are expected to experience greater levels of traffic.

Table 13: Non-residential route segments

Segment	Route	Speed limit (mph)	Length (m)	Description
London Wall Wormwood Street	A	30	540	Busy thoroughfare
Outwich Houndsditch Bevis Marks	A	30	660	Less busy but important connectors between London Wall and Aldgate High Street
Upper Street	B	30	330	Important route (A1)
Camden High Street	C	20	430	Busy, multi-lane high street (one-way)
The Cut	D	30	340	Busy high street with residential access and many pedestrians
Westminster Bridge Road	D	30	540	Important route (A302)
Vauxhall Bridge Road	E	30	1050	Important route (A202)
Horseferry	E	30	510	Mixed use route with shops and office
Exhibition Road	F	20	590	Single surface with high pedestrian usage
Queen's Gate	F	30	580	Wide street, segregated by direction with much parking (residential, but an important connector)

As seen previously, average speeds are low (table 14), with only Upper Street exceeding 20mph. Some streets, such as London Wall, Wormwood Street and Camden High Street, appear severely congested. This is supported by observations made during data collection.

Table 14: Summary statistics for non-residential segments (ordered by average speed)

Segment	Route	Observations (number of laps)	Speed limit (mph)	Average speed[15] (mph)	Standard deviation[16] (mph)
Upper Street	B	14	30	21.1	7.3
Queen's Gate	F	12	30	19.0	8.3
Outwich Houndsditch Bevis Marks	A	14	30	15.2	6.5
Exhibition Road	F	12	20	14.6	5.9
Horseferry	E	21	30	14.4	8.7
Vauxhall Bridge Road	E	21	30	14.1	9.7
Westminster Bridge Road	D	14	30	9.6	9.3
The Cut	D	14	30	8.8	6.1
Camden High Street	C	15	20	6.5	6.0
London Wall Wormwood Street	A	14	30	4.2	5.9

[15] Average speed is calculated per observation, and then averaged across all observations
[16] Standard deviation applies to the entire data set

Further analysis (table 15) shows the proportion of time spent in excess of speeds of 20mph. As would be expected, streets with lower average speeds (such as London Wall / Wormwood Street and Camden High Street) also have a large proportion of vehicle idling. Judging from observations made, this can largely be attributed to congestion on these links.

Table 15: Operating conditions of non-residential segments (ordered by proportion >20mph)

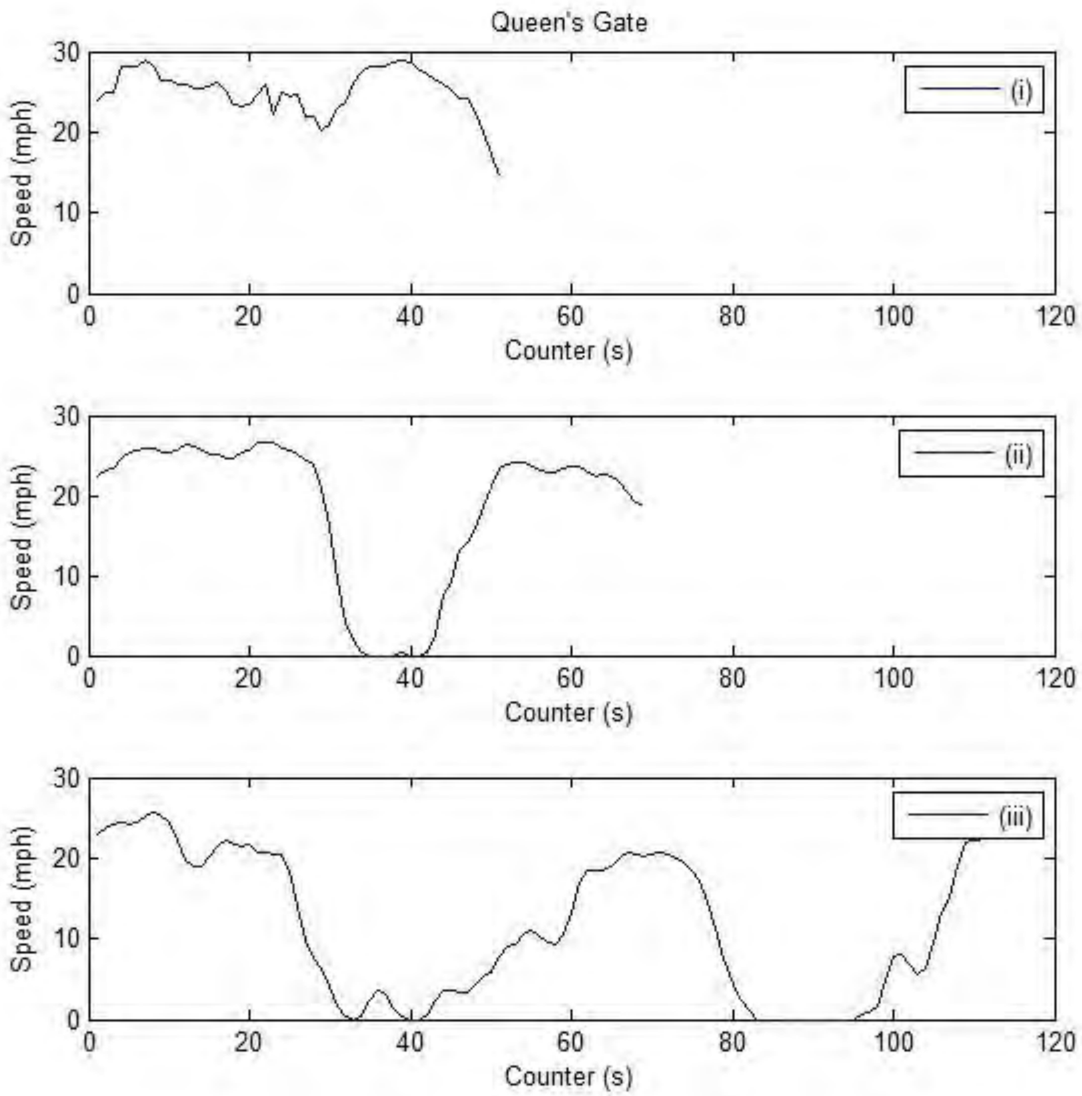
Segment	Route	Average speed (mph)	Speed limit (mph)	Average proportion idle (%)	Average proportion[17] >20mph (%)
Upper Street	B	21.1	30	2.3%	74.1%
Queen's Gate	F	19.0	30	3.0%	62.7%
Vauxhall Bridge Road	E	14.1	30	18.2%	37.9%
Horseferry	E	14.4	30	16.1%	31.7%
Outwich Houndsditch Bevis Marks	A	15.2	30	3.7%	24.3%
Westminster Bridge Road	D	9.6	30	32.6%	21.5%
London Wall Wormwood Street	A	4.2	30	48.9%	2.5%
Exhibition Road	F	14.6	20	3.9%	1.8%
Camden High Street	C	6.5	20	33.7%	1.7%
The Cut	D	8.8	30	9.3%	1.0%

Once again, solely relying on averaging speed to explain the traffic situation is shown to be misleading. Streets such as Queen's Gate often exhibit speeds over 20mph despite an average of around 19mph.

[17] Calculated for each observation and then averaged across all (un-weighted)

Viewing a speed trace of Queen's Gate for several observations (figure 21) in conjunction with the field notes gives some reasons for the variation. In observation (i) no delay is incurred; in observations (ii) and (iii) the vehicle stops for a zebra crossing (30 – 40 seconds); in observation (iii) there is a particularly long queue at the southern junction with Cromwell Road (90 seconds).

Figure 21: Queen's Gate example speed trace (route F)



5 ESTIMATION OF TAILPIPE EMISSIONS

Objective 2 (section 1.2) is related to understanding the impact of changes in driving style between 20mph and 30mph zones on tailpipe emissions of NO_X, PM_{10} and CO_2. This will be achieved by development of specific drive cycles for both 20mph and 30mph roads.

5.1 DRIVE CYCLE DEVELOPMENT

Having demonstrated the variability present in these data, emissions estimates will be constructed using a largely unconstrained data set. Drive cycles are generally implemented on a chassis dynamometer as a means of testing fuel consumption and emissions from various vehicles. It is not the intention here to mimic any existing drive cycles, but certain characteristics will be considered. Since this study is concerned with urban driving, the ECE-15 portion of the New European Driving Cycle (NEDC) is considered most relevant and is shown here to provide some context (table 16).

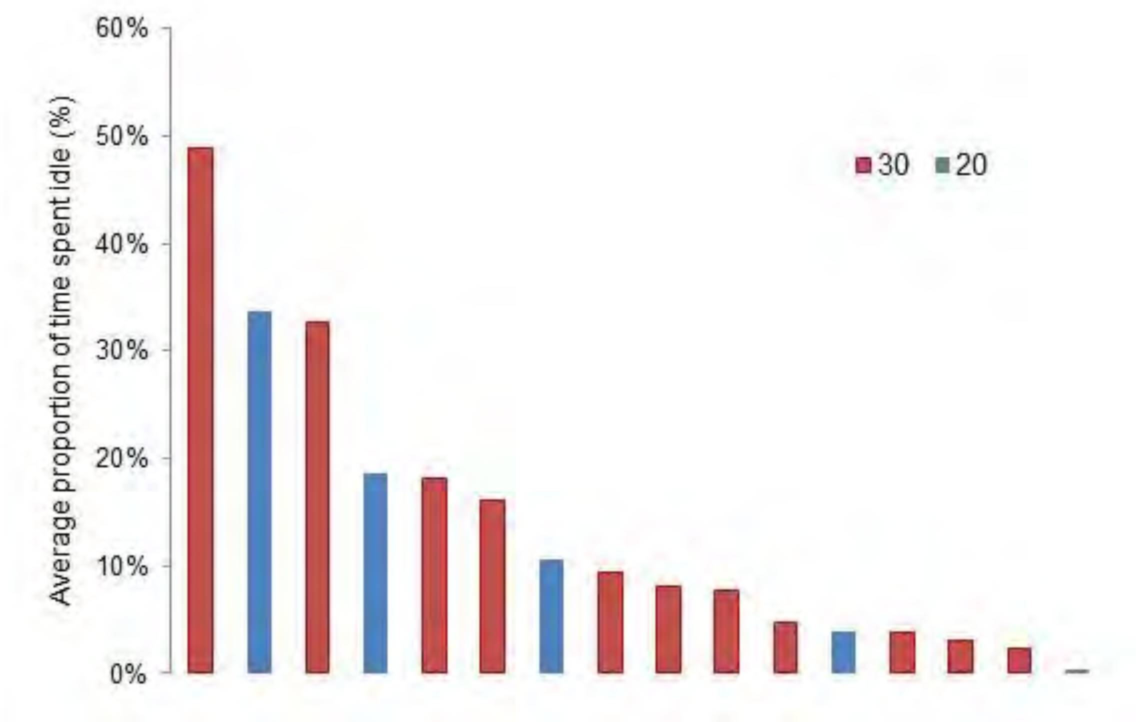
Table 16: ECE-15 urban drive cycle characteristics

ECE-15 (urban)		
Distance (m)	4,052	(4 * 1013)
Time (s)	780	(4 * 195)
Average speed (mph)	11.8	
Maximum speed (mph)	31.1	
Acceleration (% time)	21.6	
Deceleration (% time)	13.8	
Idle (% time)	35.4	
Cruise[18] (% time)	29.3	

Different drive cycles must be defined for each type of road. A key characteristic of a drive cycle is the amount of time spent in each vehicle operating mode. As discussed previously, it is expected that this is not a characteristic particularly related to speed limit. Figure 22 shows the average amount of time spent idling[19] for 16 route segments (also discussed in section 4).

[18] Described as "steady speed"
[19] Calculated for each observation and then averaged across all (un-weighted)

Figure 22: Proportion spent 'idling' by route segment and speed limit



Again, there does not appear to be any relationship between speed limit and the amount of time spent idling. As such, when constructing drive cycles for 20mph and 30mph speed limits, the following length of the drive cycle (distance) will be the key criteria considered. Time to complete will not be considered, as the same distance and lower average speed (as would be expected in 20mph zones over 30mph zones) would lead to a longer time to complete. Although time spent in each vehicle operating mode will be calculated, it will not be specifically matched.

As a first pass, the data was limited so that each route segment was represented once (table 17).

Table 17: Initial drive cycle construction

Drive cycle	**20mph**	**30mph**	**ECE-15**
Distance[20] (m)	3,250	10,871	4,052
Time (s)	793	2,076	780
Average speed (mph)	9.2	11.7	11.8
Maximum speed (mph)	24.7	29.7	31.1
Acceleration (% time)	5.0	6.9	21.6
Deceleration (% time)	4.4	6.7	13.8
Idle (% time)	25.3	21.6	35.4
Cruise (% time)	65.2	64.8	29.3

[20] Approximate, based on 1Hz speed data measured in m/s

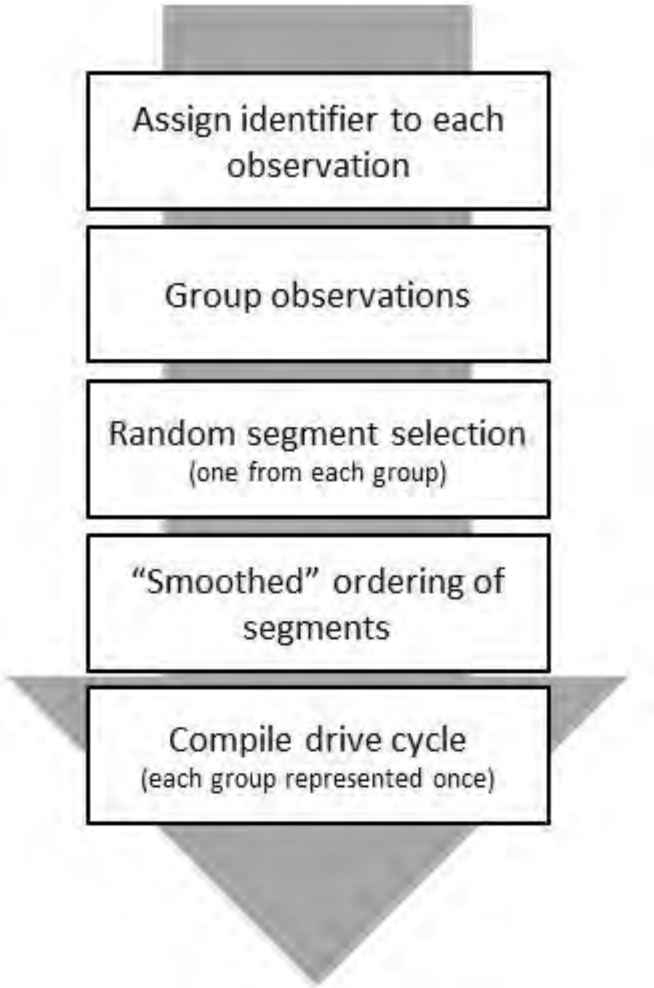
When compared to the existing regulatory cycle, ECE-15, the most striking difference is in the proportion of time spent in the acceleration and deceleration vehicle operating modes[21]. Since the drive cycles developed here are based on empirical data, equivalence with ECE-15 is not sought. However, this does highlight the unsuitability of relying on such drive cycles for site specific analyses.

Drive cycles have been developed by randomly sampling the data available to provide several variations. The process for each is shown in figure 23. Each observation is assigned a unique identifier relating to the day of data collection, the route, the segment and the lap. These observations are then grouped:

- For the 20mph data set, the groupings are based only on the geographical segment
- For the 30mph data set, the segments are aggregated into groups based on length

Observations are then randomly selected from each group to provide a series (stratified random sampling). In order to minimise the occurrence of unrealistic acceleration and deceleration behaviour, the observations are ordered so that "start" and "end" speed of each observation match closest with adjacent observations.

Figure 23: Drive cycle development process



[21] This assumes comparable definitions for each mode of vehicle operation

In all, 16 drive cycles were developed for 20mph (A-H) and 30mph roads (J-R). These are described in table 17 and displayed in figures 24, 25, 26 and 27. Whilst time to complete, average speed and time spent in each vehicle operating mode varies over the different cycles, distance is within a 250m range (8% of the lower bound).

Table 18: Generated 20mph and 30mph drive cycles

20 mph	A	B	C	D	E	F	G	H
Distance[22] (m)	3225	3224	3230	3216	3256	3247	3223	3250
Time (s)	794	742	811	727	691	754	701	553
Average speed (mph)	9.1	9.7	8.9	9.9	10.5	9.6	10.3	13.1
Maximum speed (mph)	20.2	27.0	22.2	26.1	23.9	22.0	24.5	24.8
Acceleration (% time)	3.4%	3.6%	5.5%	3.6%	3.0%	4.8%	5.0%	3.4%
Deceleration (% time)	3.8%	3.2%	4.6%	4.8%	1.6%	4.8%	4.9%	3.8%
Idle (% time)	29.1%	25.7%	29.0%	22.4%	27.1%	24.5%	20.1%	8.9%
Cruise (% time)	63.7%	67.4%	60.9%	69.2%	68.3%	65.9%	70.0%	83.9%
30 mph	**J**	**K**	**L**	**M**	**N**	**P**	**Q**	**R**
Distance (m)	3253	3287	3462	3256	3334	3274	3453	3312
Time (s)	613	570	712	425	632	560	535	646
Average speed (mph)	11.9	12.9	10.9	17.1	11.8	13.1	14.4	11.5
Maximum speed (mph)	29.1	28.9	28.1	28.2	27.5	28.2	28.0	29.5
Acceleration (% time)	8.2%	7.2%	6.3%	6.8%	9.2%	6.4%	10.1%	5.7%
Deceleration (% time)	7.3%	7.0%	3.8%	5.6%	8.1%	5.7%	9.5%	7.0%
Idle (% time)	14.5%	23.5%	23.3%	11.3%	22.5%	17.0%	6.9%	17.0%
Cruise (% time)	70.0%	62.3%	66.6%	76.2%	60.3%	70.9%	73.5%	70.3%

[22] Approximate, based on 1Hz speed data measured in m/s

Figure 24: Speed trace of 20mph drive cycles (A, B, C, D)

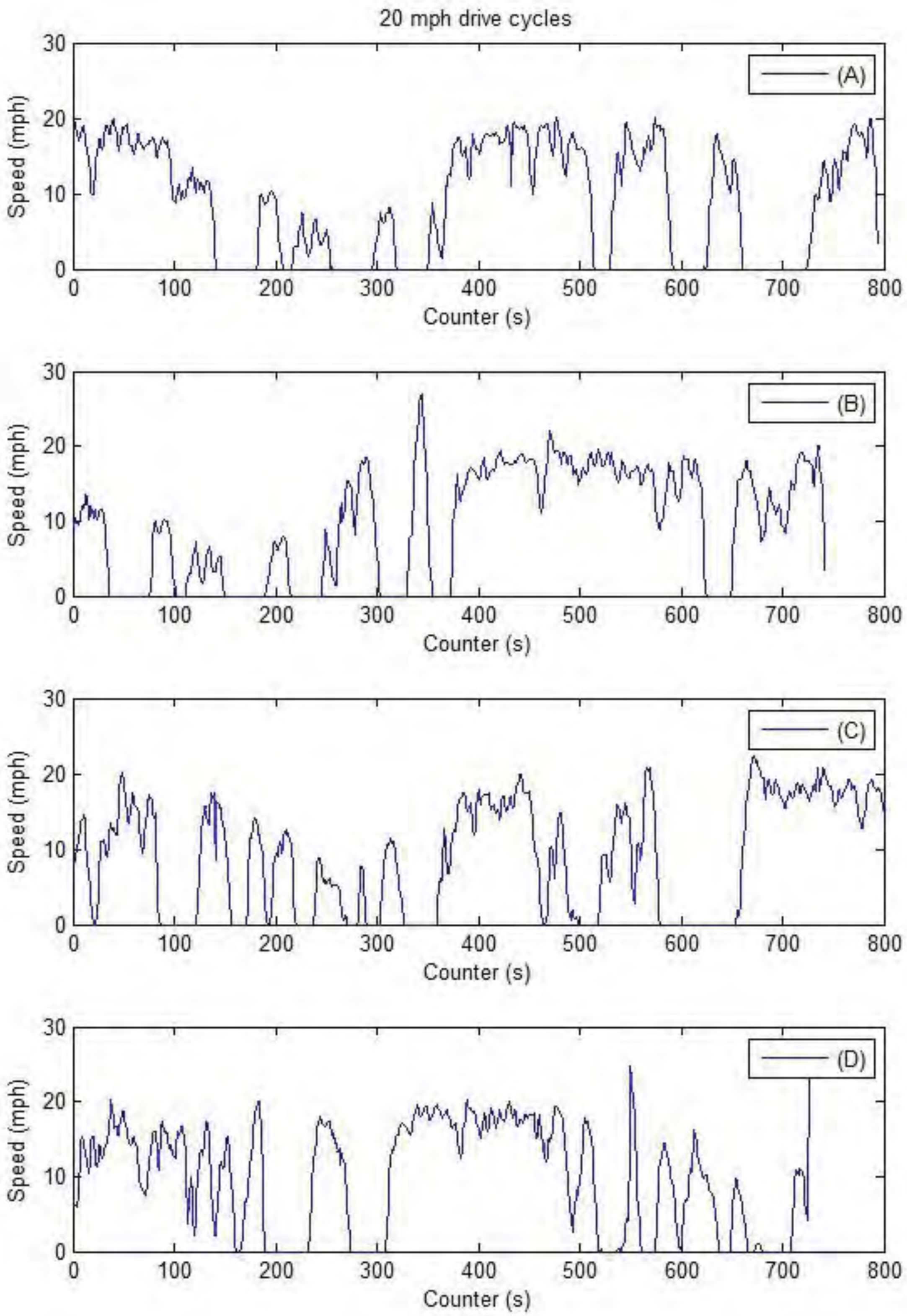


Figure 25: Speed trace of 20mph drive cycles (E, F, G, H)

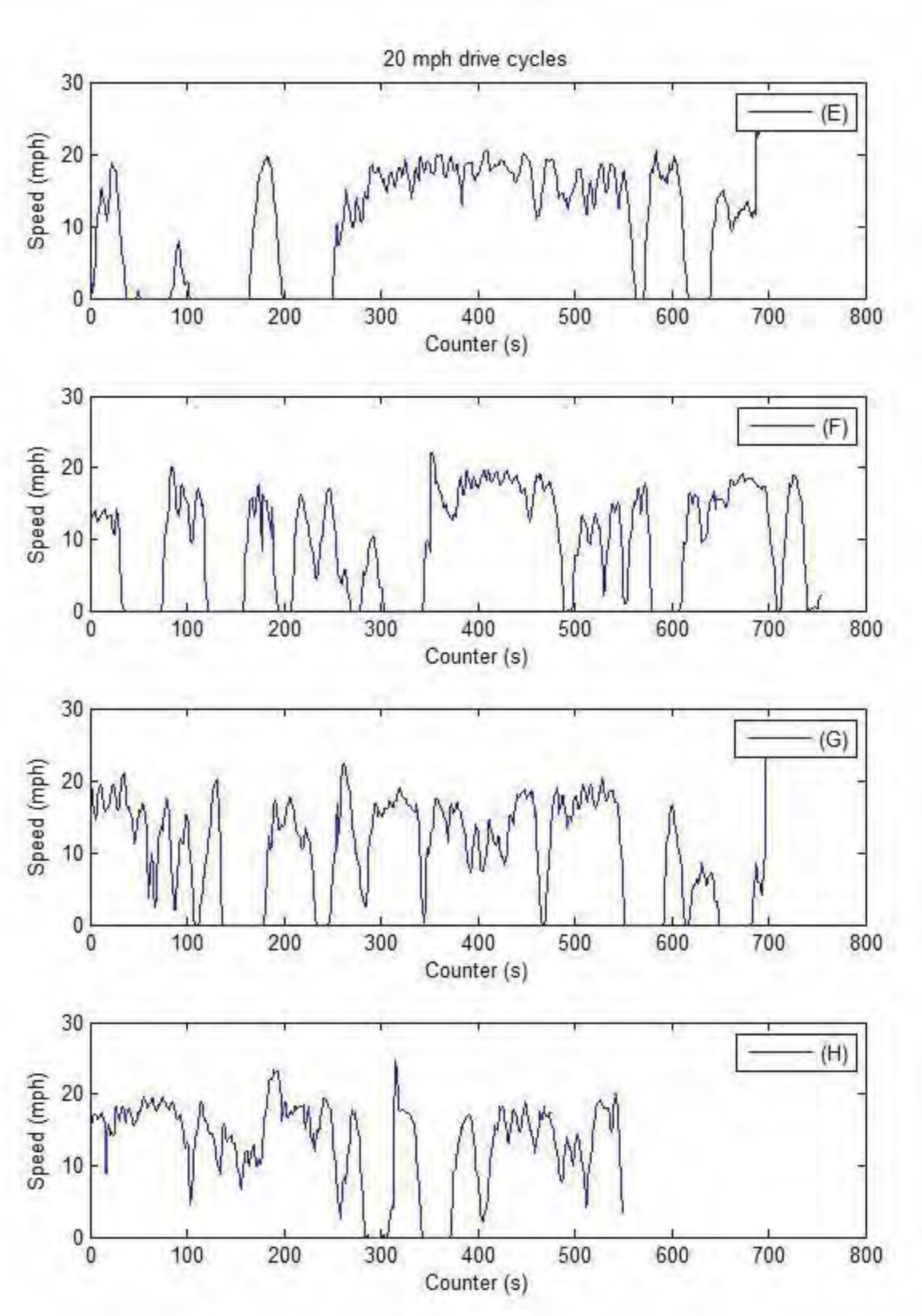


Figure 26: Speed trace of 30mph drive cycles (J, K, L, M)

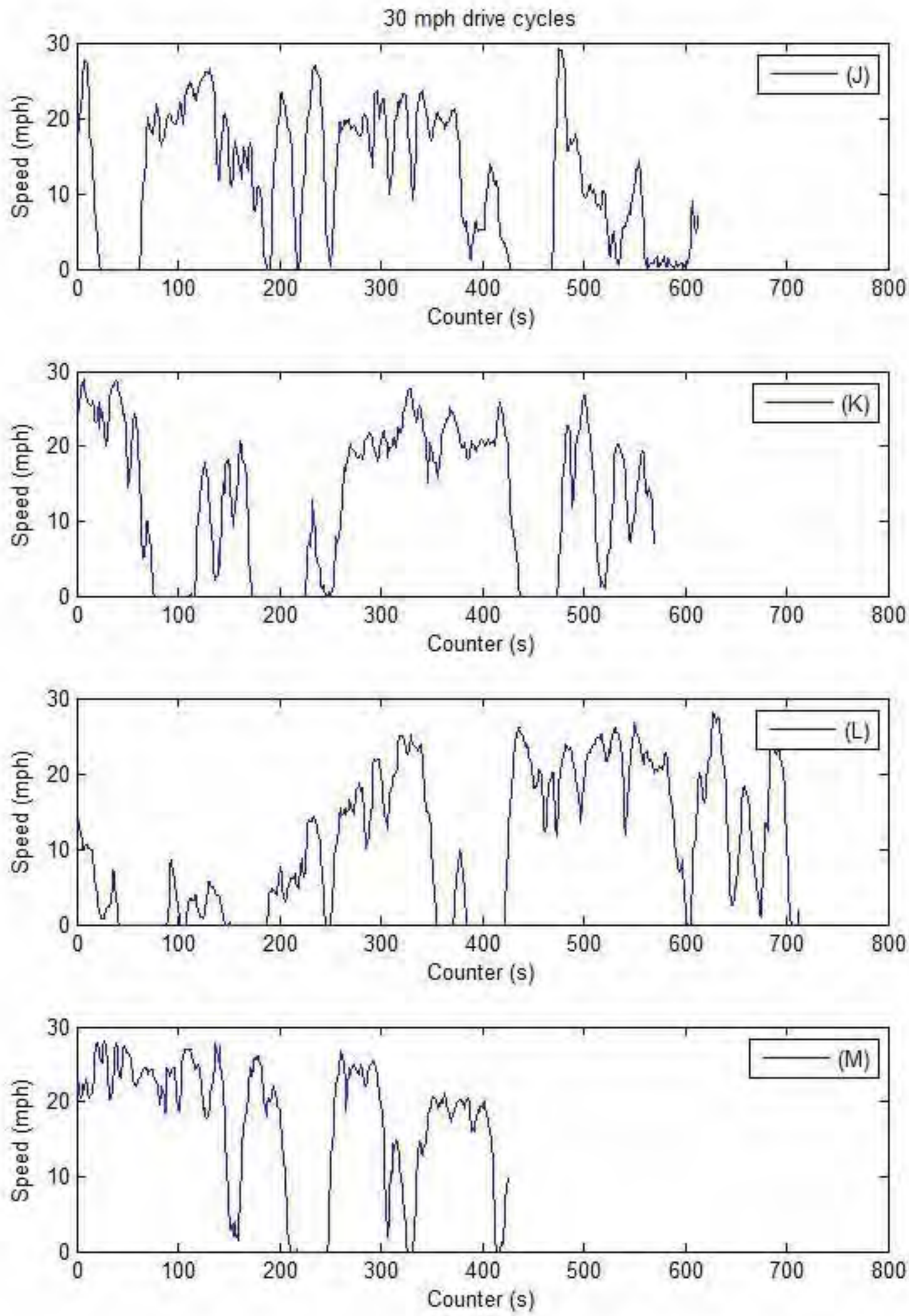
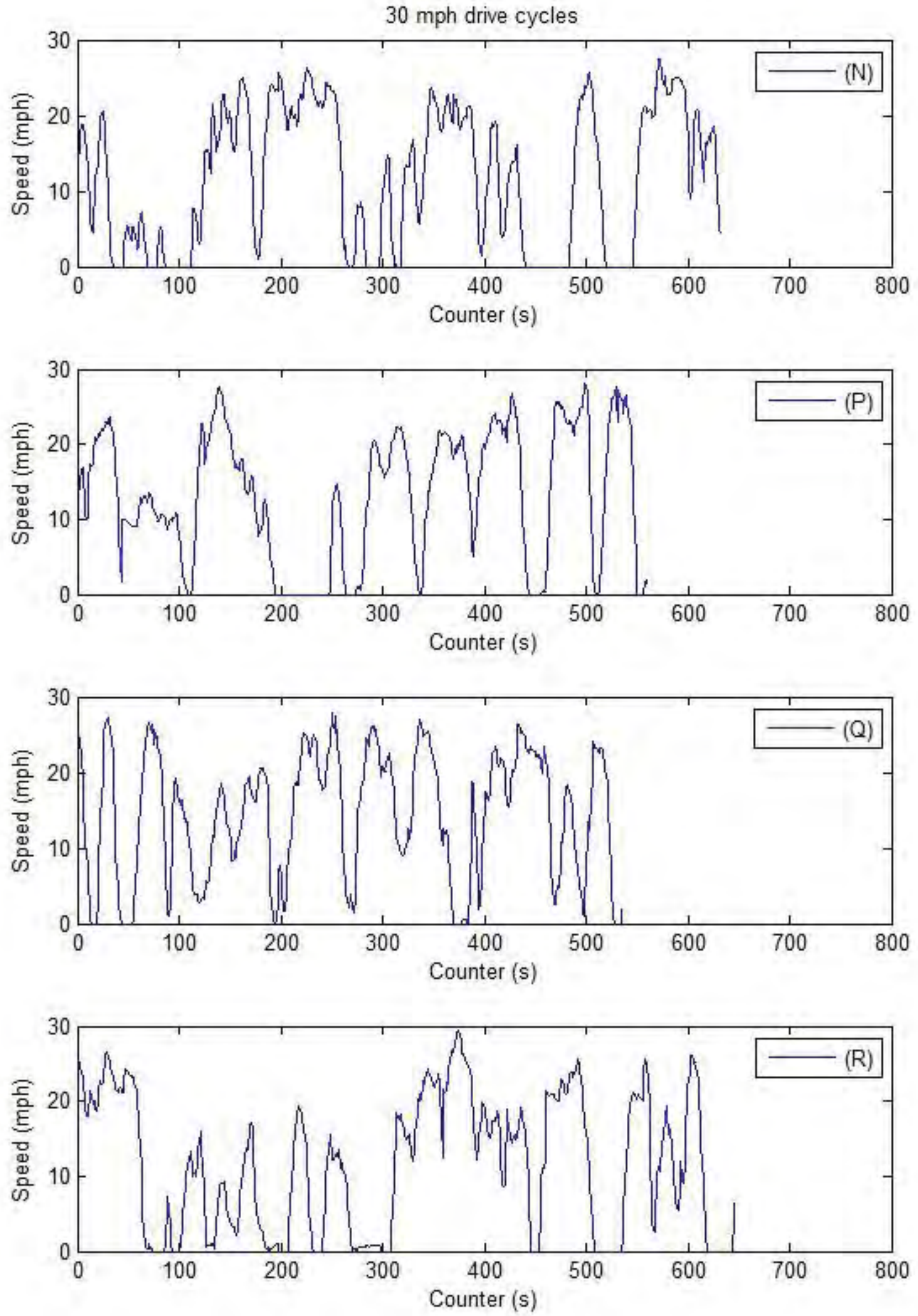


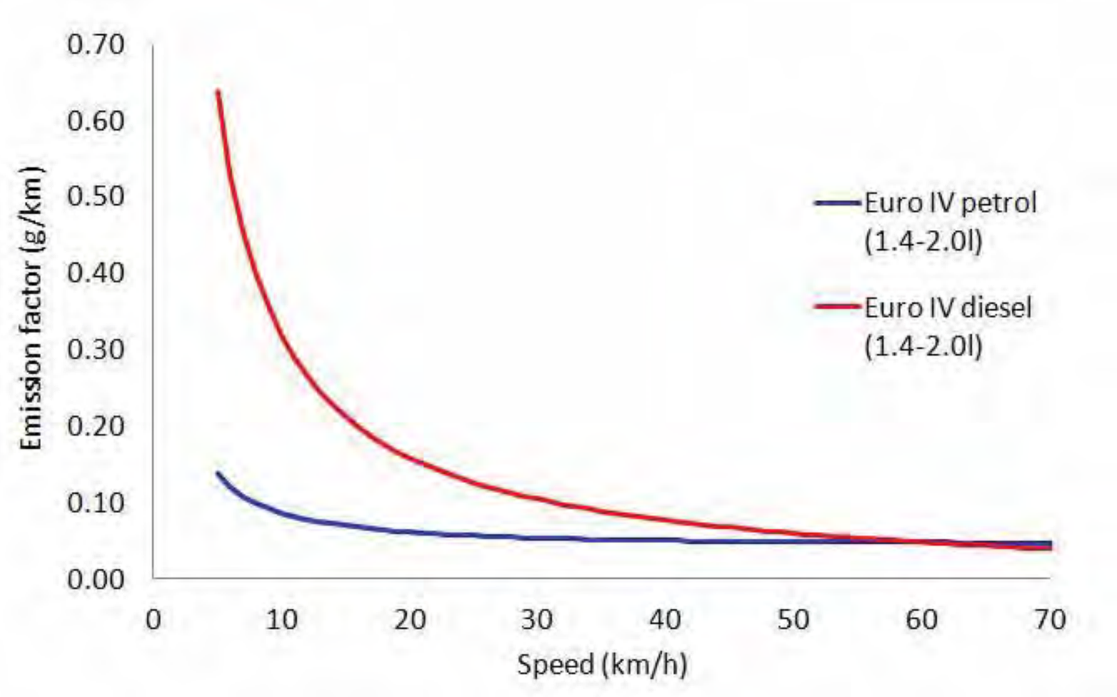
Figure 27: Speed trace of 30mph drive cycles (N, P, Q, R)



5.2 MODELLING EMISSIONS

A standard method for assessing pollutant emissions for road traffic is through the use of average speed models [6, 14]. The key explanatory variables utilised by such models are the vehicle type, fuel type and average speed. By including information regarding traffic levels and fleet composition, estimation of the contribution of road traffic to pollutant emissions can be formulated. An example is shown in figure 28.

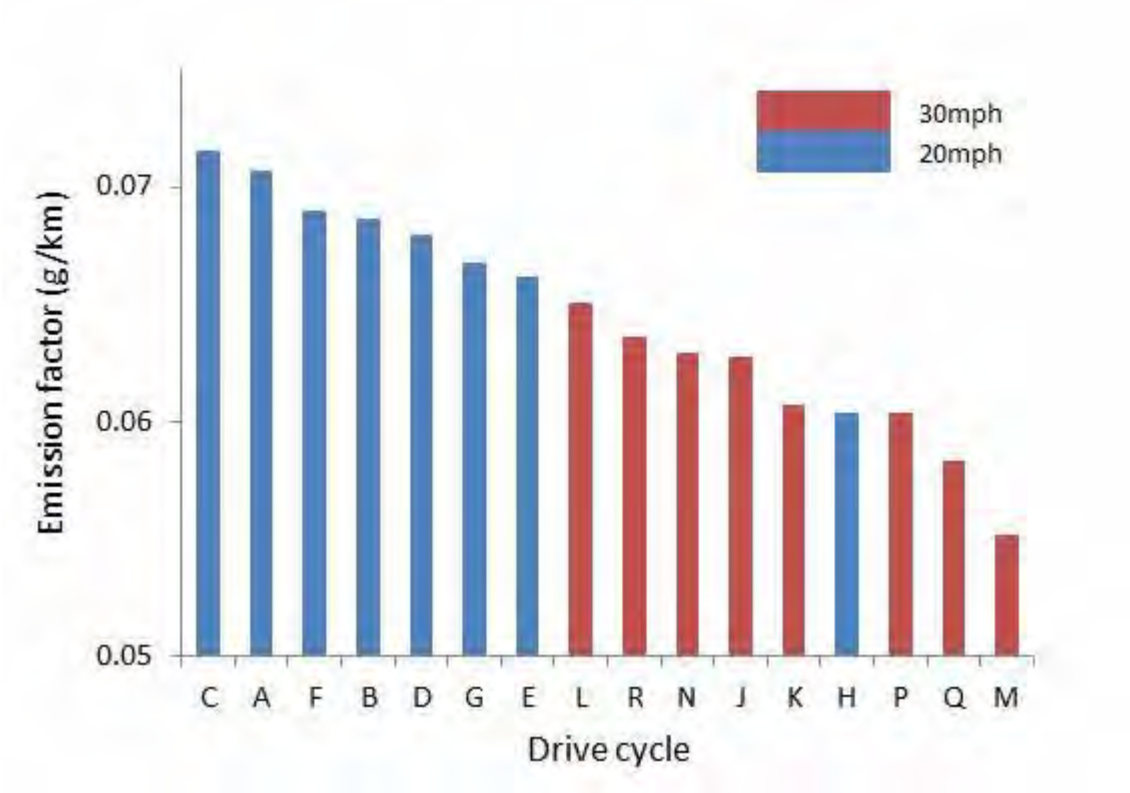
Figure 28: Vehicle emission curve for NO_X [generated from 15]



Considering the average speeds alongside parameters such as acceleration and deceleration observed during each of the drive cycles formed (table 18), it is concluded that this method is not suitable for this analysis. Figure 27 illustrates the application of this; the 30mph drive cycles generally exhibit higher average speeds and are therefore shown to have a lower estimated emission factor than 20mph drive cycle results. Given the dynamic behavior of the vehicle, this is an insufficient level of detail.

Instead, an instantaneous emission model is used. By incorporating vehicle dynamics on a per time-step basis (rather than an average), a more reliable estimate of vehicle emissions will be generated.

Figure 29: Estimated NO_X emission factors for typical[23] petrol car using average speed method[24]



The measured drive cycles can be used to estimate emissions from a single road vehicle. AIRE (Analysis of Instantaneous Road Emissions) is an instantaneous emissions database for estimating particulate matter, total carbon and oxides of nitrogen. Whilst AIRE is usually applied to the outputs of microsimulation models, conversion tools have been written to allow a single drive cycle to be analysed for emissions. The drive cycle is first interpolated to a frequency of 2Hz, before being converted to the correct file type. AIRE is then configured for a range of vehicle and fuel types.

In order to make a fair comparison, emissions are normalised by route length and an emission factor (mass per unit time) is calculated[25]. Each emission factor is a composite of the data from each of the drive cycles described in section 5.1 (A – H for 20mph roads, J – R for 30mph roads).

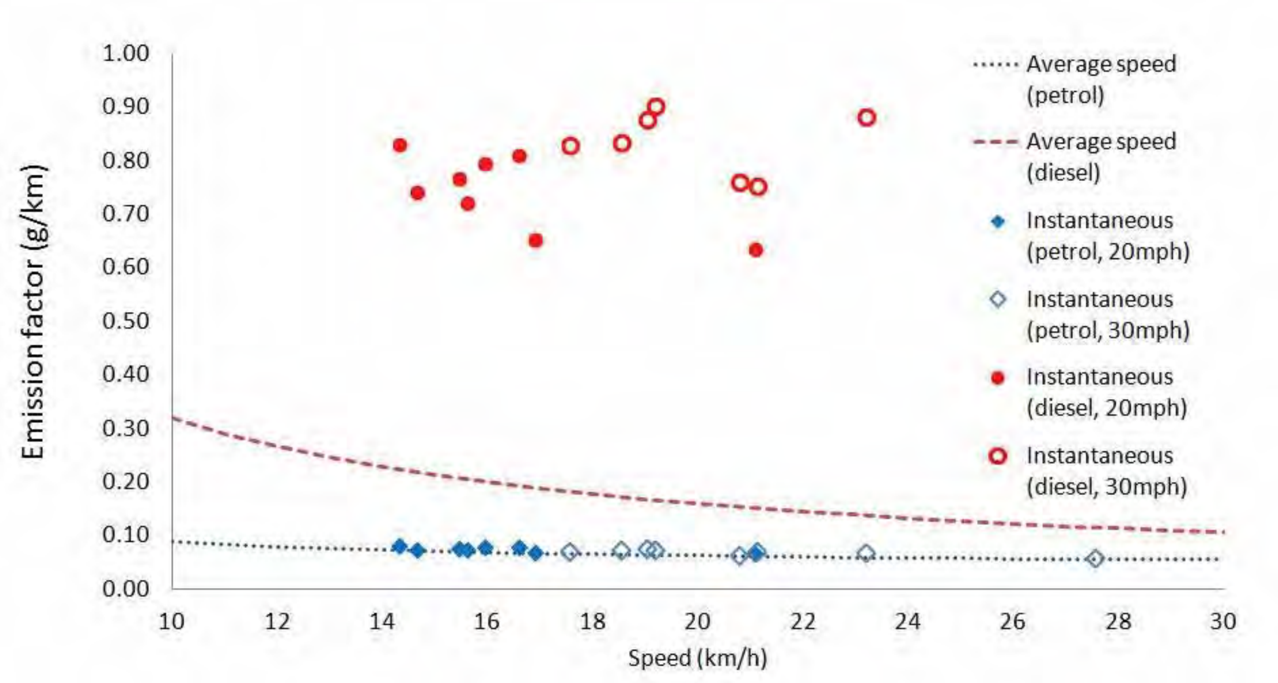
The range of emission factors generated can be seen in figure 30. A direct comparison can be made with the emission factors generated by the average speed method (previously shown for petrol vehicles in figure 29). Whilst for petrol vehicles the range of values appear approximately equivalent, the average speed method appears to substantially underestimate NO_X emissions from diesel vehicles. This is a significant result. Figure 28 demonstrates the importance of capturing lower speeds for diesel vehicles in particular, as this is where greater levels of NO_X are emitted.

First of all, it can be seen that the range of values is approximately equivalent. However, the order has changed. Drive cycle A was previously ranked second (ordered by highest emission factor) and is now ranked sixth. Drive cycle E was previously ranked seventh, but is now ranked twelfth. Whilst

23 EURO IV, 1.4 – 2.0 litre petrol passenger car under 2.5 tonnes
24 Using the recommended methodology for establishing emission factors in the UK [15]
25 Mass of carbon dioxide is estimated from total carbon

this does not provide particular insight into vehicle emission rates on different types of roads, it once again highlights the inadequacy of average speed models for small area studies.

Figure 30: Comparison of instantaneous and average speed methods for estimating NO_X emission rates[26]



By adjusting the model parameters, results are presented for a range of fuel and vehicle types (table 19 and 20). These are common types that make up a large proportion of the passenger car fleet. Euro V vehicles are not represented in this model; whilst a correction factor could be applied, it has been decided that the trends present are more important, and so the model is used in default form.

Table 19: Estimated emission rates – petrol vehicles

Vehicle type	Drive cycle speed limit	NO_X (g/km)	PM_{10} (g/km)	CO_2 (g/km)
1.4 – 2.0 litre, EURO III	20	0.0967	0.00255	299.16
1.4 – 2.0 litre, EURO III	30	0.0806	0.00283	278.05
Impact of 20mph drive cycle		+20.1%	-9.7%	+7.6%
1.4 – 2.0 litre, EURO IV	20	0.0726	0.00218	271.95
1.4 – 2.0 litre, EURO IV	30	0.0673	0.00237	266.35
Impact of 20mph drive cycle		+7.9%	-8.3%	+2.1%
< 1.4 litre, EURO IV	20	0.0817	0.00252	220.31
< 1.4 litre, EURO IV	30	0.0723	0.00275	219.59
Impact of 20mph drive cycle		+13.0%	-8.3%	+0.3%
> 2.0 litre, EURO IV	20	0.0580	0.00096	402.90
> 2.0 litre, EURO IV	30	0.0564	0.00093	374.59
Impact of 20mph drive cycle		+2.9%	+3.7%	+7.6%

26 EURO IV, 1.4 – 2.0 litre petrol passenger car under 2.5 tonnes

Table 20: Estimated emission rates – diesel vehicles

Vehicle type	Drive cycle speed limit	NO_X (g/km)	PM_{10} (g/km)	CO_2 (g/km)
1.4 – 2.0 litre, EURO III	20	1.4096	0.04123	195.62
1.4 – 2.0 litre, EURO III	30	1.5371	0.04566	197.57
Impact of 20mph drive cycle		-8.3%	-9.7%	-1.0%
1.4 – 2.0 litre, EURO IV	20	0.7437	0.01758	201.58
1.4 – 2.0 litre, EURO IV	30	0.8104	0.01917	203.48
Impact of 20mph drive cycle		-8.2%	-8.3%	-0.9%
> 2.0 litre, EURO IV	20	0.4875	0.01584	319.85
> 2.0 litre, EURO IV	30	0.4859	0.01527	303.27
Impact of 20mph drive cycle		+0.3%	+3.8%	+5.5%

The results suggest imposing a 20mph speed limit would have mixed effects on emissions from a single vehicle, and it can be supposed, ambient air quality. Estimated NO_X is increased for petrol vehicle and decreased for diesel (with the expectation of a negligible increase for large diesels). Given the higher rates for diesel vehicles, and the increasing makeup of diesels in the vehicle fleet, this is a significant result. In the case of PM, a larger decrease (8-10%) is seen for all vehicles up to 2.0 litres in size. Large vehicles exhibit an increase in emissions, but not as substantial. The inefficiencies in fuel consumption of travelling at lower speeds are demonstrated by the trend in CO_2 emission factors.

In general it is concluded that it is incorrect to state that a 20mph speed restriction will lead to greater pollutant emissions for vehicles. Another significant aspect of this analysis is that average speed models do not have the resolution required to assess emissions in urban environments.

It should be reiterated that this analysis is relevant to per vehicle emissions, and does not account for any associated impact of implementing a speed restriction, such as reduced flows (due to re-routing or congestion).

5.3 MODEL VALIDATION

Modelling outputs are based on laboratory testing and should ideally be validated against real-world emissions measurements. In this instance, tailpipe emissions data from a light duty vehicle in London has been compared to that estimated from the generated drive cycles. The data has been provided by Emissions Analytics [16], who employ high-resolution portable emissions measurement systems (PEMS) in order to assess on-road emissions and fuel consumption.

In this case, data from a single vehicle (comparable to the one used in this study) was extracted and processed. The data was restricted to eliminate the effect of cold start emissions, and then used to generate a series of drive cycles of similar length to those already developed (table 21).

Table 21: Generated drive cycles from PEMS reference data

Real-world data	S	T	U	V	W
Distance[27] (m)	3251	3233	3197	3112	3261
Time (s)	384	550	393	422	709
Average speed (mph)	18.9	13.1	18.2	16.5	10.3
Maximum speed (mph)	28.9	31.9	32.9	29.9	27.0
Acceleration (% time)	2.3%	1.5%	1.8%	2.6%	0.1%
Deceleration (% time)	2.3%	2.5%	4.8%	3.6%	1.0%
Idle (% time)	5.2%	16.5%	12.0%	4.7%	21.9%
Cruise (% time)	90.1%	79.5%	81.4%	89.1%	77.0%

When compared to the 20mph and 30mph generated drive cycles, the real-world data generally shows a smaller proportion of in the acceleration and deceleration phase of operation. As such, a direct comparison is difficult. A more comprehensive study where similar routes are driven to those included in this study would be enlightening.

In order to validate the methodology applied, AIRE can be used to estimate emissions from the real-world drive cycles, which can be compared to the data collected through PEMS. Results are shown in table 22. Whilst PEMS data provides figures for total CO_2 (mass), AIRE estimates total carbon (mass) – as such, a conversion factor is applied.

[27] Approximate, based on 1Hz speed data measured in m/s

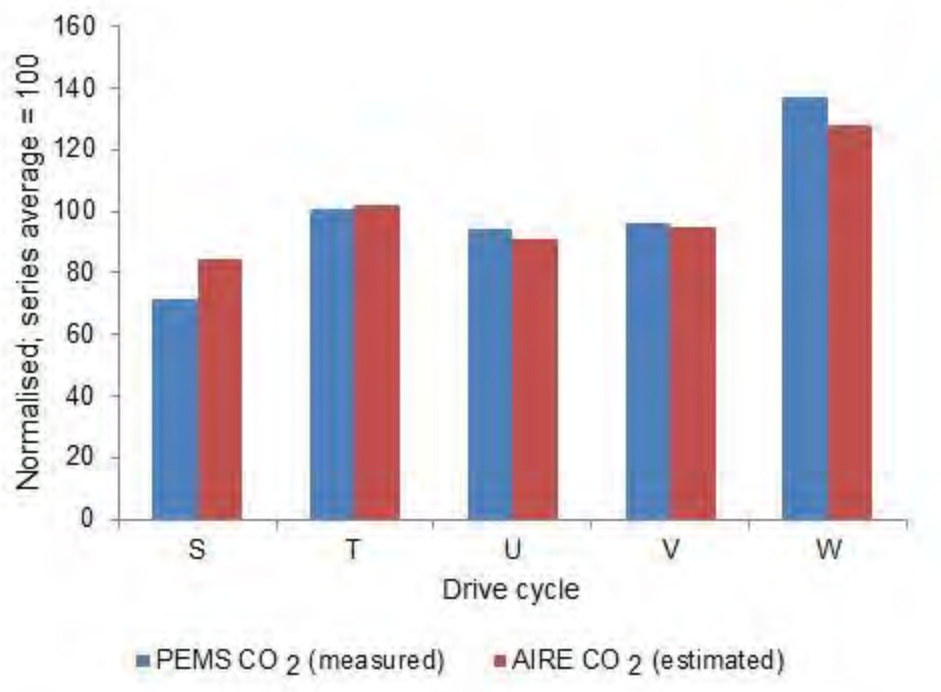
Table 22: Measured and estimated pollutant emissions

PEMS reference data	S	T	U	V	W
Measured CO_2 (g)	389.9	548.6	513.0	523.5	747.3
Estimated CO_2 (g)	540.4	651.4	584.2	607.9	819.5
Measured NO_X (mg)	207.3	212.2	196.5	243.9	590.5
Estimated NO_X (mg)	163.9	177.6	175.5	185.0	218.5

Some differences in absolute figures can be attributed to the model utilising fleet average figures, and to the characteristics of the individual vehicle. Of key importance in this instance are the trends inherent. These determine whether or not a methodology such as this is suitable for answering research questions, such as assessing which scenario is better.

Figures 31 and 32 show normalised data[28], allowing the trend to be viewed more clearly. In the case of CO_2, the modelling methodology gives a good representation of what is seen in the real-world. In the case of NO_X, the relationship is not as good. This is likely to be related to the emissions class (as AIRE does not include Euro V vehicles) and the particularly unusual characteristics of drive cycle W (see table 21). Removing this gives a better agreement (figure 33), but highlights the shortcomings of the modeling methodology when assessing unusual situations.

Figure 31: Measured and modelled CO_2 emissions (normalised)



[28] A base has been set whereby the average for the series is equal to 100

Figure 32: Measured and modelled NO_X emissions (normalised)

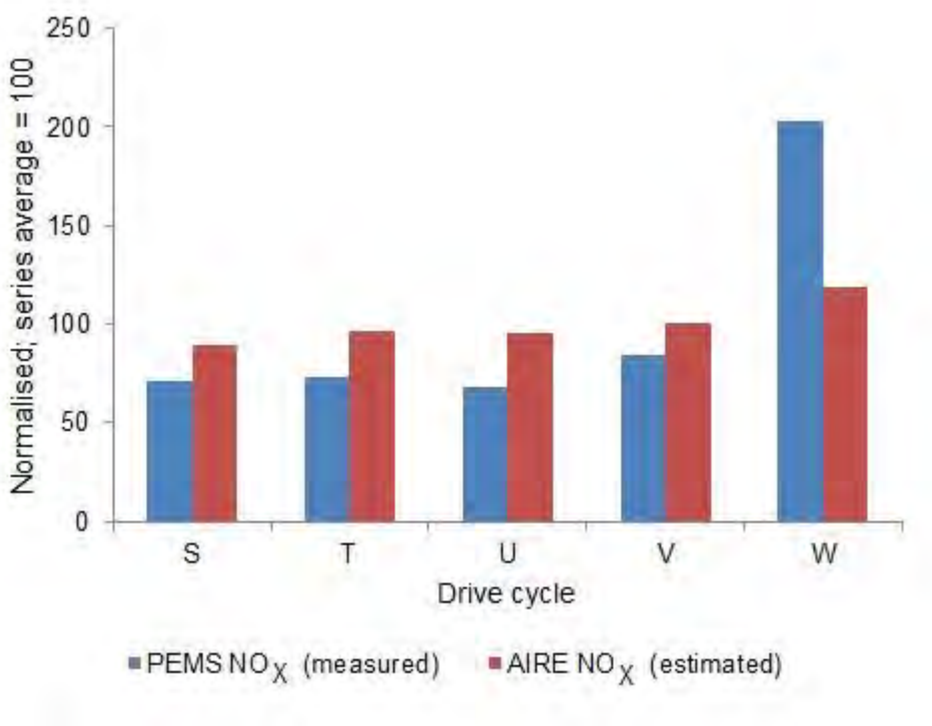
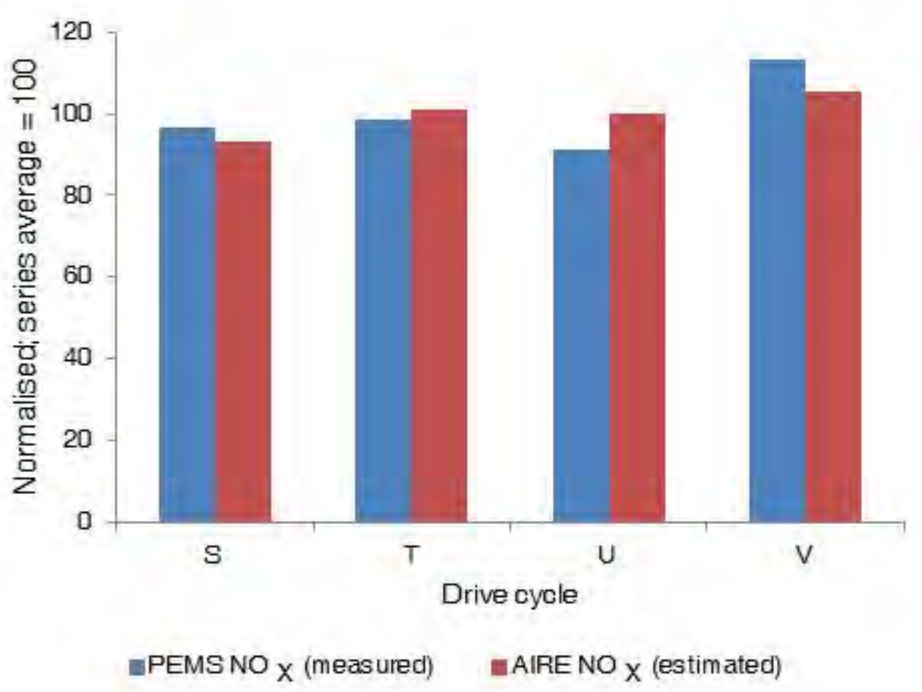


Figure 33: Measured and modelled NO_X emissions (constrained, normalised)



6 SPEED CONTROL METHODS

Objective 3 (section 1.2) is concerned with the impact that different methods of speed control can have on emissions. Three general categories were determined: vertical deflection, horizontal deflection and psychological.

Local Transport Note 1/07 [3] provides advice on the implementation of traffic calming schemes. It also makes clear the importance of considering the impact of various traffic calming measures on vehicle emissions. Several research projects are referenced, with two key points:

- The impact on emissions is related to both the average speed of traffic and the amount of speed variation
- Increases in per vehicle emissions may be offset by a reduction in the volume of traffic

Given the intention of all traffic calming schemes to reduce average speed of traffic, it is reasonable to suppose that the measures with the least detrimental impact on vehicle emissions would be those that induce the least variation in speed.

6.1 METHODOLOGY

Estimated emissions from a range of different roads will be compared. Road segments as previously defined (section 4.1) will be selected on the basis of exhibiting different traffic calming measures. For some links, the amount of traffic may be seen as being more influential to the behaviour of (and emissions from) a single vehicle (e.g. where the link is highly congested). In these cases, the link has not been considered for inclusion. In total, 10 segments were chosen, representing a range of different traffic calming methods. These are shown in table 23.

Table 23: Speed control characteristics of selected segments

Segment	Route	Length (m)	Speed limit	Speed control characteristics
Liverpool Road	B	391	20	Speed cushions, humped zebra crossing
Furlong Road	B	169	20	Speed humps
Islington Park Street	B	190	20	Traffic island (width restriction), speed cushions
Royal College Street	C	370	20	Speed cushions
The Cut	D	343	30	Humped pedestrian crossings, raised junction (speed table)
Marshalsea Road	D	227	20	None
Union Street	D	454	20	Speed cushions, one-way priority section
John Islip Street	E	567	30	Speed cushions, lane narrowing (hatching, traffic islands)
Exhibition Road	F	590	20	Single surface
Queen's Gate	F	577	30	None

For each segment, several typical observations (laps) were selected. Given that journey time (time to complete the segment for each lap) is normally distributed, the four observations closest to the mean value were chosen. These were then pre-processed before estimation of emissions estimation using AIRE. A single value was obtained for each segment by averaging multiple estimates.

6.2 ESTIMATED EMISSION FACTORS

Given the differing lengths of segments, direct comparison of estimated emissions would not be worthwhile. Instead, emission factors were generated for each segment. These are shown in table 24 and 25, ordered by CO_2 emission factor, alongside commonly used reference emission factors.

Table 24: Generated pollutant emission factors for a petrol passenger car[29]

Segment	Speed limit	Characteristic	NO_X (g/km)	PM_{10} (g/km)	CO_2 (g/km)
The Cut	30	Humped pedestrian crossings, raised junction (speed table)	0.0785	0.002676	318.55
Furlong Road	20	Speed humps	0.0961	0.002751	310.06
Marshalsea Road	20	None	0.0641	0.002343	248.91
Union Street	20	Speed cushions, one-way priority section	0.0696	0.002108	242.34
Islington Park Street	20	Traffic island (width restriction), speed cushions	0.0673	0.002299	240.71
John Islip Street	30	Speed cushions, lane narrowing (hatching, traffic islands)	0.0584	0.002367	229.95
Exhibition Road	20	Single surface	0.0627	0.001963	216.37
Queen's Gate	30	None	0.0538	0.001940	198.89
Liverpool Road	20	Speed cushions, humped zebra crossing	0.0585	0.001875	195.02
Royal College Street	20	Speed cushions	0.0472	0.001559	169.23

[29] Engine size 1.4 – 2.0 litre, Euro IV standard

Table 25: Generated pollutant emission factors for a diesel passenger car[30]

Segment name	Speed limit	Characteristic	NO_X (g/km)	PM_{10} (g/km)	CO_2 (g/km)
Furlong Road	20	Speed humps	0.9911	0.0222	245.45
The Cut	30	Humped pedestrian crossings, raised junction (speed table)	1.0602	0.0216	236.94
Marshalsea Road	20	None	0.7223	0.0189	188.08
Islington Park Street	20	Traffic island (width restriction), speed cushions	0.7271	0.0186	184.63
Union Street	20	Speed cushions, one-way priority section	0.7101	0.0170	184.24
John Islip Street	30	Speed cushions, lane narrowing (hatching, traffic islands)	0.7414	0.0191	183.95
Exhibition Road	20	Single surface	0.5402	0.0159	161.64
Queen's Gate	30	None	0.5671	0.0157	154.86
Liverpool Road	20	Speed cushions, humped zebra crossing	0.5013	0.0151	149.66
Royal College Street	20	Speed cushions	0.4093	0.0126	123.72

Generally, the lower emission rates (mass per unit distance) are seen on streets where it would be expected that speed can be better maintained. This is consistent with accepted understanding.

6.3 SPECIFIC EXAMPLES

Several worthwhile comparisons can be made to illustrate the differences between speed control methods. Liverpool Road displays lower estimated emissions than Furlong Road, despite the same speed limit and location. This can be attributed to the difference in speed calming method. Whilst both employ vertical deflection, in the case of Liverpool Road it is predominantly speed cushions, whilst on Furlong Road it is speed humps (photograph 2).

[30] Engine size 1.4 – 2.0 litre, Euro IV standard

Photograph 2 (L-R): Speed cushions on Liverpool Road and speed hump on Furlong Road

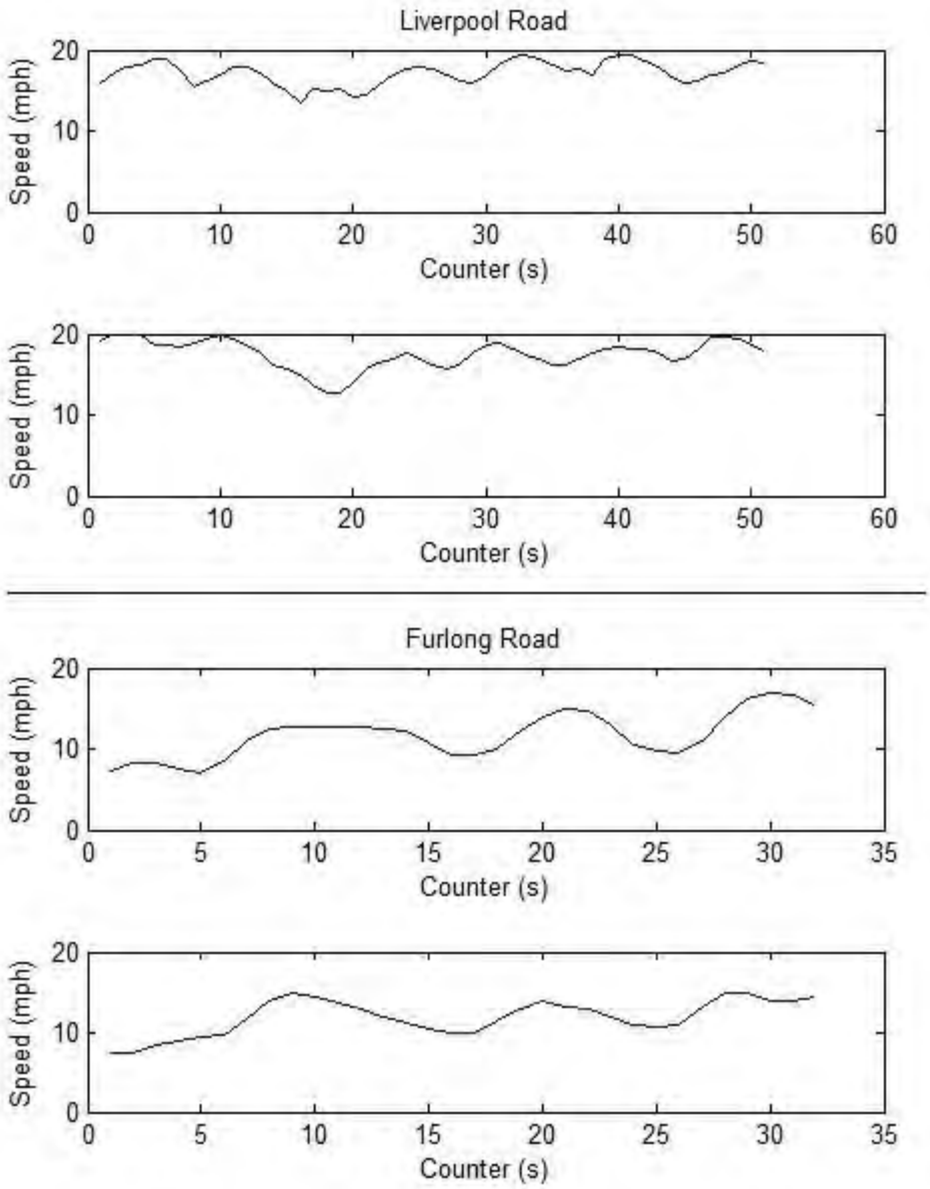
Table 26: Liverpool Road and Furlong Road emission factors[31]

Segment name	Speed limit	Fuel type	NO_X (g/km)	PM_{10} (g/km)	CO_2 (g/km)
Liverpool Road	20	Petrol	0.0585	0.001875	195.02
Furlong Road	20	Petrol	0.0961	0.002751	310.06
			+64%	*+47%*	*+59%*
Liverpool Road	20	Diesel	0.5013	0.015148	149.66
Furlong Road	20	Diesel	0.9911	0.022223	245.45
			+98%	*+47%*	*+64%*

Speed humps are higher and usually span the width of the carriageway, therefore requiring additional deceleration. This is illustrated by the speed time traces in figure 34. Furlong Road displays both a lower average speed and a greater range of speeds, indicating the additional deceleration required.

[31] Engine size 1.4 – 2.0 litre, Euro IV standard

Figure 34: Liverpool Road and Furlong Road vehicle speed trace

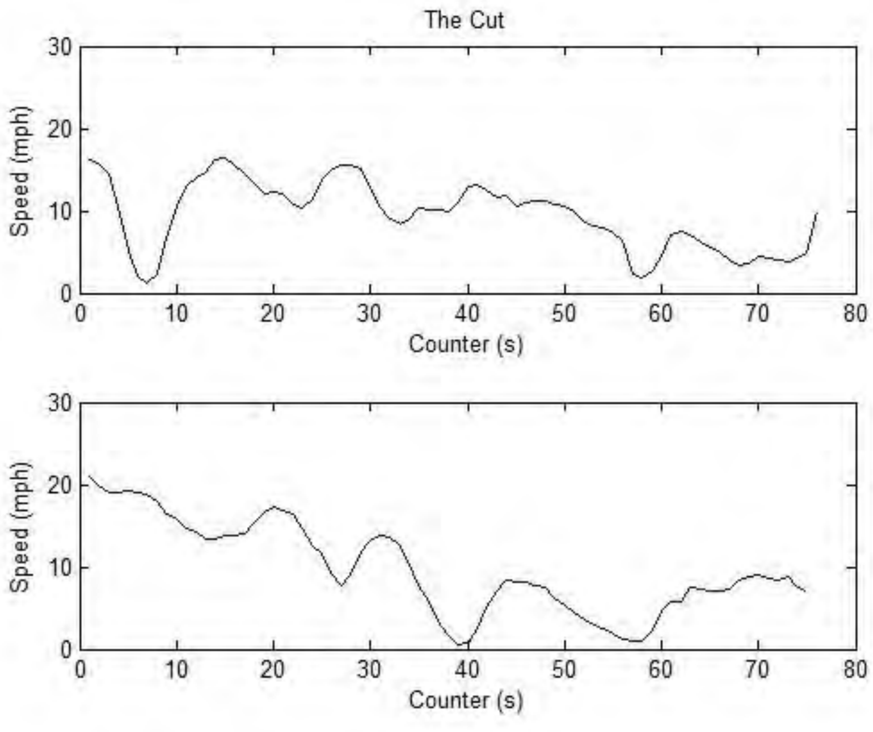


Despite a 30mph speed limit, The Cut exhibits the worst emission rate for CO_2. However, due to raised areas, frequent zebra crossings (photograph 3), high cycling use and on-street parking, speed levels are reduced.

Photograph 3: Pedestrian (zebra) crossing on The Cut

This is shown in speed traces for two observations (figure 29). Speed does not generally exceed 20mph, and there are frequent instances of deceleration.

Figure 35: The Cut vehicle speed trace



In the case of Marshalsea Road and Exhibition Road, there is little variability in speed due to the absence of any particular traffic calming features. However, calculated emission rates are influenced by the presence of a junction towards the end of the segment (after around 70 seconds on Exhibition Road, 25 seconds on Marshalsea Road). This is illustrated by example speed traces (figure 36).

Figure 36: Example vehicle speed trace for Exhibition Road and Marshalsea Road

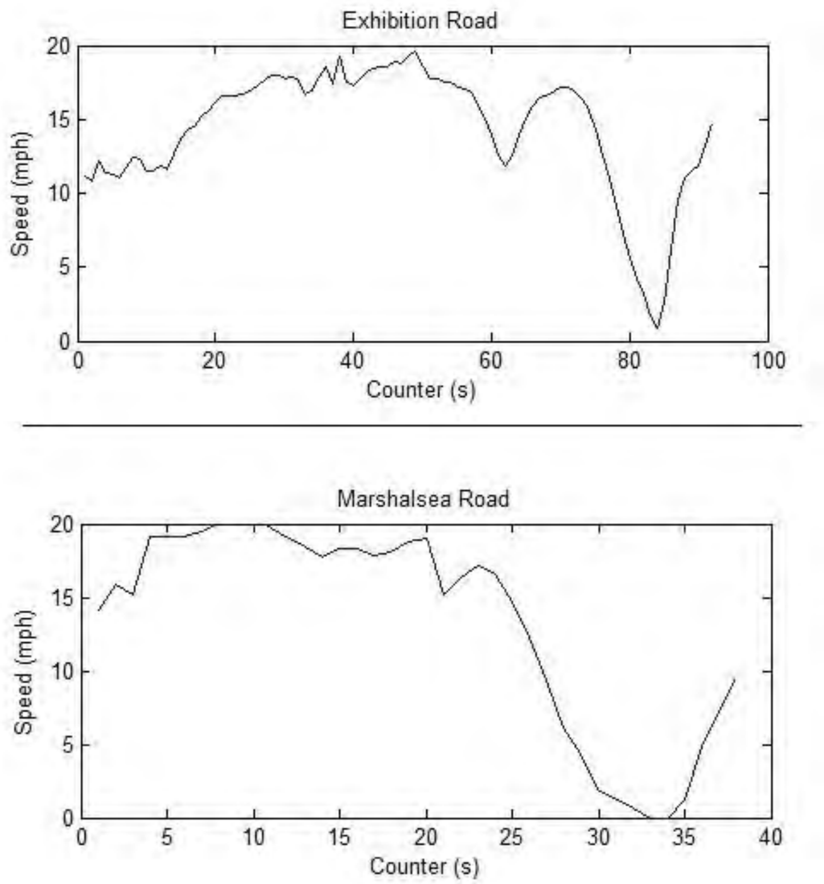


Table 27: Exhibition Road and Marshalsea Road emission factors[32]

Segment name	Speed limit	Fuel type	NO_X (g/km)	PM_{10} (g/km)	CO_2 (g/km)
Exhibition Road	20	Petrol	0.0627	0.001963	216.37
Marshalsea Road	20	Petrol	0.0641	0.002343	248.91
			+2%	*+16%*	*+13%*
Exhibition Road	20	Diesel	0.5402	0.015854	161.64
Marshalsea Road	20	Diesel	0.7223	0.018925	188.08
			+34%	*+19%*	*+16%*

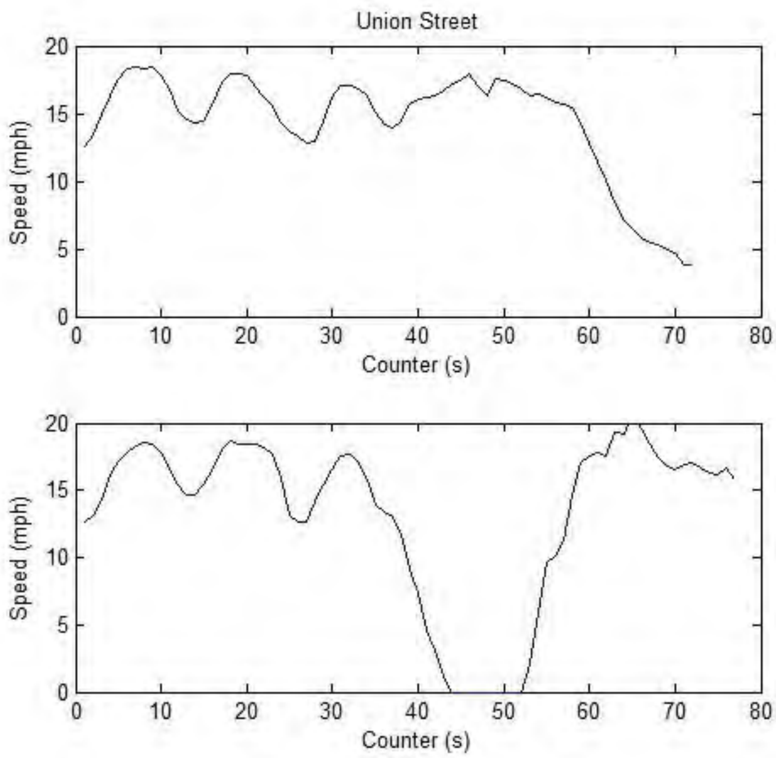
Union Street has both vertical deflection (speed cushions and humped sections) and a one-way section (priority working).

[32] Engine size 1.4 – 2.0 litre, Euro IV standard

Photograph 4: Speed cushions on Union Street

The influence of this can be seen by examining two speed traces (figure 37). In both traces the characteristic variation in speeds surrounding vertical deflection can be seen. However, only in the latter can the influence of a priority one-way section be seen.

Figure 37: Union Street vehicle speed trace



Results here are consistent with accepted understanding on the behaviour of vehicles and the generation of pollutant emissions in urban areas. Vehicles are often seen to exhibit a greater variability in speed on links with vertical deflection than those without. However, the influence of such traffic calming features when compared to other traffic management features, such as pedestrian crossings and signalized junctions, is not thought to be as large.

Table 28: Range of emissions estimates for Union Street[33]

	NO_X (g/km)	PM_{10} (g/km)	CO_2 (g/km)
Average	0.06963	0.00211	66.09
Highest estimate	0.07585	0.00232	70.60
	+8.2%	*+9.1%*	*+6.4%*
Lowest estimate	0.06088	0.00186	58.40
	-12.6%	*-11.9%*	*-11.6%*

[33] Engine size 1.4 – 2.0 litre, Euro IV standard

7 BRAKE AND TYRE WEAR

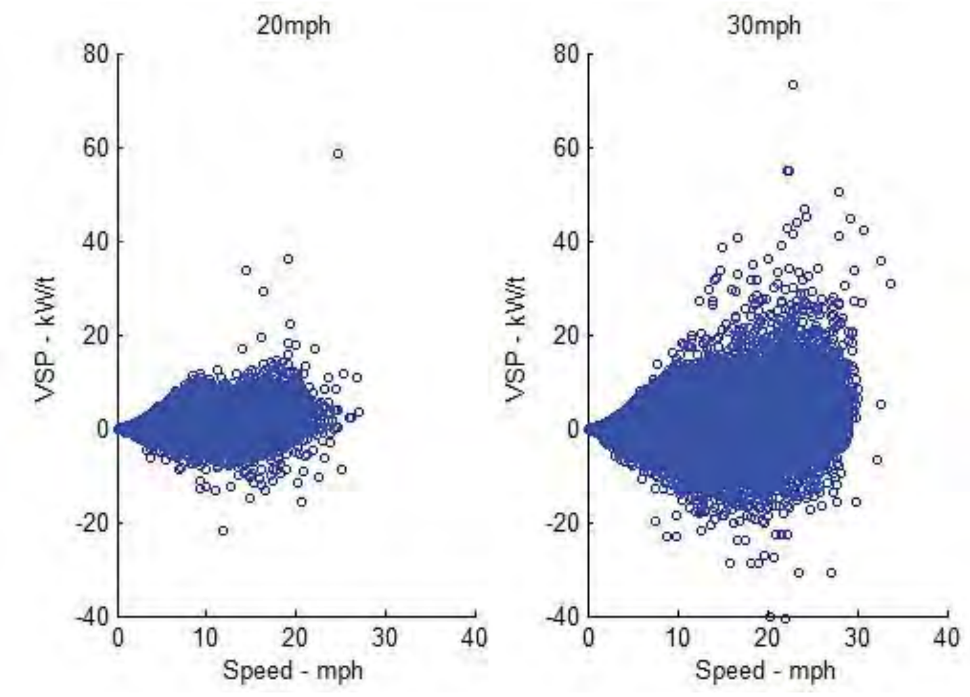
Objective 4 (section 1.2) is related to the impact of 20mph speed limits on brake and tyre wear emissions. Standard methodologies [15] for calculating tyre and brake wear emissions are on a per distance basis by vehicle type. This is sensitive only to fleet mix and traffic levels, and not to individual vehicle dynamics. Studies have indicated the importance of vehicle speed, tyre condition, accelerating and decelerating behaviour and vehicle speed for brake and tyre wear. Tyre and brake wear is also strongly linked to vehicle type due to the influence of weight. One European study [16] demonstrated the inverse linear relationship between mean speed and emissions of tyre and brake matter. This would suggest that where links have a lower average speed, brake and tyre emissions would also be lower. Although this is a generally sensible result, it does not directly address the phases of vehicle operation that are linked to brake and tyre wear emissions (acceleration, braking and cornering).

A useful measure of the vehicle operating condition is vehicle specific power (VSP). VSP combines information specific to the vehicle, such as mass and the coefficient of drag, as well operating conditions, such as air density, headwind speed and gradient and the dynamic behaviour (speed and acceleration) to calculate the power[34] required [17]. By combining typical operating parameters and standard conditions, a simplified equation suitable for a light duty vehicle has been proposed [18]:

$$VSP = v * (1.1 * a + 0.132) + \ 0.000302 * v^3$$

where *v* represents vehicle speed in m/s, and *a* is vehicle acceleration in m/s^2. Figure 38 demonstrates the smaller range of power demand incurred on 20mph roads compared to 30mph roads.

Figure 38: Range of vehicle specific power and speed by road type



[34] VSP is defined as the instantaneous power per unit mass of the vehicle

High positive VSP is associated with strong acceleration, and would be expected to correlate to higher tyre wear rates per unit time. High negative VSP is associated with strong decelerations that would be expected to lead to increased brake wear rates as well as increased tyre wear rates. When considering the overall emissions per unit distance (i.e. in g/km), the length of time spent in each of these operating modes is also important. The smaller proportion of time spent decelerating on a 20mph road (as shown in chapter 4, Figure 10) would suggest that tyre and brake wear would also be less at the lower speed limit in mass per unit distance terms.

From the observed distributions it is therefore to be expected that the less dynamic drive cycles associated with 20mph roads would lead to reduced levels of PM emissions from non-exhaust sources. However, further study of this area is needed to enable quantitatively robust estimates to be made. One possibility for this might be to engage with vehicle fleet operators to measure the mass loss from tyres and brake components between services. If combined with knowledge of the operating cycles of the fleet vehicles (e.g. from an automatic vehicle location system) from a sufficient number of vehicles then a model relating non-exhaust PM emission rates to particular operating patterns might be developed. A detailed examination of this possibility was unfortunately beyond the scope of the present investigation.

8 SUMMARY OF FINDINGS

8.1 PROJECT OBJECTIVES

The project will seek to understand:

1. The difference in driving styles between 20mph and 30mph roads
2. The impact of this change on estimated tailpipe emissions of NO_X, PM_{10} and CO_2
3. The impact on emissions of different methods of speed control on urban roads
4. The impact on emissions from brake and tyre wear of a 20mph zone

8.2 PROJECT FINDINGS

In section 4 it was concluded that the driving styles (as characterised by the vehicle operating mode and distribution of cruise speeds) are different on 20mph roads as compared to 30mph roads. This was achieved by splitting the measured vehicle trajectories into segments based on speed limit and further aggregating the data. Whilst time of day and day of the week was not seen to be particular importance, site-specific analysis showed the variation in recorded vehicle behaviour at and between sites. In particular, residential streets with 30mph speed limits were often shown to have vehicle speed not exceeding 20mph. This was also true of heavily trafficked non-residential streets.

Section 5 detailed the development of London-specific 20mph and 30mph drive cycles for use with instantaneous emissions databases. The effects of a 20mph speed restriction on were shown to be mixed, with particular benefit seen for emissions of particulate matter and for diesel vehicles. The methodology was validated by consideration of real-world tailpipe emissions test data. It was therefore concluded that air quality is unlikely to be made worse as a result of 20mph speed limits on streets in London. This analysis is suitable for per-vehicle emission rates, and does not consider secondary effects such as congestion.

Speed control methods were investigated in greater detail in section 6. Streets where traffic flow was more likely to be interrupted were shown to have higher emission rates. However, this could not always be attributed to traffic calming measures (particularly vertical deflection) and was often the result of other traffic management infrastructure (pedestrian facilities and junctions).

Section 7 discussed the potential for lower speed limits to impact brake and tyre wear emissions. In general it is accepted that the lower demand for power at lower speed limits is likely to be beneficial to emissions of this type.

8.3 FURTHER WORK

There is great potential for further work in this area. Although the modeling work here has been validated, application of high-resolution portable emissions measurement systems to specific cases in London would yield useful data that could better help answer these research questions. A particular deficiency in current understanding is around tyre and brake wear. These are a significant proportion of particulate matter is urban areas, and better knowledge of the influences on their emission will further inform traffic management and control decisions.

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APPENDICES

APPENDIX I: ROUTE INFORMATION

Route	Street	Borough
A	London Wall (EB) / Camomile Street	CoL
	Outwich Street / Houndsditch	CoL
	St Botolph Street / Aldgate High Street	CoL
	Bevis Marks	CoL
	Bishopsgate	CoL
	Threadneedle Street	CoL
	Lothbury / Gresham Street	CoL
	Wood Street	CoL

Route	Street	Borough
B	Liverpool Road	Islington
	Furlong Road	Islington
	Holloway Road	Islington
	Upper Street	Islington
	Cross Street	Islington
	Essex Road	Islington
	Canonbury Road	Islington
	Canonbury Lane	Islington
	Islington Park Street	Islington

Route	Street	Borough
C	St Pancras Way	Camden
	Royal College Street	Camden
	Camden Street	Camden
	Camden High Street	Camden
	Kentish Town Road	Camden

Route	Street	Borough
D	Union Street	Southwark
	The Cut	Southwark / Lambeth
	Baylis Road	Lambeth
	Westminster Bridge Road	Lambeth / Southwark
	Borough Road	Southwark
	Borough High Street	Southwark
	Marshalsea Road	Southwark

Route	Street	Borough
E	Horseferry Road	Westminster
	Buckingham Gate	Westminster
	Vauxhall Bridge Road	Westminster
	John Islip Street	Westminster

Route	Street	Borough
F	Exhibition Road	K&C / Westminster
	Kensington Road	Westminster
	Queen's Gate	K&C / Westminster
	Onslow Gardens / Old Church Street	K&C
	King's Road	K&C
	Sydney Street / Onslow Square	K&C
	Thurloe Place	K&C

APPENDIX II: GENERATED DRIVE CYCLE EMISSION FACTORS

Engine size 1.4 – 2.0 litre, Euro IV standard

PETROL			
	NO_X (g/km)	PM_{10} (g/km)	CO_2 (g/km)
A	0.07159	0.00207	276.46
B	0.07158	0.00212	271.55
C	0.07812	0.00230	298.35
D	0.07567	0.00234	283.56
E	0.06793	0.00200	252.62
F	0.07369	0.00220	279.44
G	0.07685	0.00235	282.91
H	0.06537	0.00202	230.69
J	0.07118	0.00255	288.09
K	0.06299	0.00230	257.93
L	0.06875	0.00231	278.48
M	0.05740	0.00209	218.77
N	0.07320	0.00250	284.66
P	0.06819	0.00229	256.85
Q	0.06604	0.00255	270.45
R	0.07069	0.00241	275.59

DIESEL			
	NO_X (g/km)	PM_{10} (g/km)	CO_2 (g/km)
A	0.7416	0.0168	201.24
B	0.7205	0.0171	199.41
C	0.8288	0.0186	220.36
D	0.7956	0.0189	211.89
E	0.6530	0.0162	186.79
F	0.7666	0.0178	206.13
G	0.8095	0.0190	212.84
H	0.6339	0.0163	173.97
J	0.9029	0.0206	219.29
K	0.7614	0.0185	195.88
L	0.8308	0.0187	208.28
M	0.6363	0.0169	169.46
N	0.8793	0.0202	220.11
P	0.7544	0.0185	198.44
Q	0.8835	0.0206	207.14
R	0.8347	0.0194	209.24