Supplemental Information Emissions, Performance and Design of UK Passenger Vehicles

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Sample data for the compiled dataset is shown in SI Table 1.

SI Table 1: Three samples of raw LDV data in the CAP dataset.

| CAP Variable          | Sample 1 | Sample 2 | Sample 3          |
|----------------------|----------|----------|-------------------|
| CAP                  | 2623     | 2624     | 4405              |
| LDV Manufacturer     | AUDI     | AUDI     | BMW               |
| LDV Model            | A6 Saloon| A6 Saloon| 3 Series          |
| LDV Derivative       | 2.5 Quattro 4dr Sport | 2.5 Quattro 4dr Sport Auto | 335i M Sport 4dr Step Auto |
| Fuel Type            | Diesel   | Diesel   | Petrol            |
| Years                | 2000-2001| 2000-2001| 2008-2012         |
| Engine Size [cc]     | 2496     | 2496     | 2979              |
| AFD Method           | DI Turbo | DI Turbo | II Turbo          |
| Fuel Economy [mpg]   | 35.3     | 31.7     | 32.5              |
| Kerb Weight [kg]     | 1645     | 1680     | 1550              |
| Retail Price [GBP]   | 24,340   | 25,532   | 30,430            |
| Compression Ratio    | 19.5:1   | 19.5:1   | 10.2:1            |
| Performance [0-62 mph]| 9.70     | 10.5     | 5.80              |
| Number Cylinders     | 6        | 6        | 6                 |
| Bore [mm]            | 78.3     | 78.3     | 84.0              |
| Stroke [mm]          | 86.4     | 86.4     | 89.6              |
Supplemental Design Trends

Air and fuel delivery design trends from 2001 to 2011 are shown in SI Figures 1 and 2.

SI Figure 1: Relative availability of LDVs by air-delivery systems, fuel type and year. CI-Naturally Aspirated (NatA) vehicles are represented in the “Other” category. T = Turbocharged.

SI Figure 2: Relative availability of LDVs by fuel-delivery system, fuel type and year. SI – NotAv refers to SI vehicles whose fuel delivery system was not specified.
The mean bore-to-stroke ratio are shown by air and fuel delivery system for 2001 to 2011 in SI Figure 3.

SI Figure 3: Annual mean bore-stroke ratios for SI and CI LDVs by air (dashed line) and fuel (solid line) systems. Erratic regressions for SI - Supercharged, CI - NatA, CI - II and SI - DI attributed to sample bias.

**Mean Piston Speed**

Mean piston speed ($S_p$) of the engine is influenced by inertial loads, resistance to airflow and engine friction. Equation 3 (Chon & Heywood, 2000), where $L$ denotes stroke length and $N$ denotes engine speed. Heywood & Welling (2009) note that the speed at which SI maximum power occurs ($S_{p,\text{max}}$) is influenced by the choking limit during the intake stroke. Brake power is restricted to a maximum value at $S_{p,\text{max}}$, which has led to additional valves, variable valve timing or lift to increase this limit. Additionally, frictional losses increase with engine speed, which is represented with the combination of Equations 2 and 3 within Equation 4.

$$S_{p,\text{max}} = 2LN_{\text{max}} \quad \text{(SI 1)}$$

$$P_{b,\text{max}} = 2\pi NT = \text{BMEP}_{\text{p,\text{max}}} \cdot V_d \cdot \frac{S_{p,\text{max}}}{n_r} \cdot \frac{2L}{2L} \quad \text{(SI 2)}$$

Increasing the number of valves and introducing variable valve timing improve the breathing capabilities of non-boosted engines (Heywood, 1988). Improved breathing reduces the work required to pump air into the engine and increase the maximum operating speed of the engine. The maximum speed that the piston can travel is limited by the rate at which air can be inducted. Vehicle manufacturers modified SI-NatA engines in this manner to increase maximum mean piston speed, $S_p$ (MMPS) as shown in SI Table 2. Naturally aspirated vehicles saw an increased MMPS of 8.6% over the decade. Conversely boosted engines (CI-T and SI-T) slightly decreased over the decade as airflow is not limited within such systems (Heywood & Welling, 2009). The MMPS is lower in CI LDVs, since SI engines require
higher engine speeds to achieve equivalent levels of power and torque. The increased engine MMPS of naturally aspirated SI engines allows for higher power output, thus enabling engine downsizing or better vehicle performance.

SI Table 2: Maximum Mean Piston Speed (MMPS) by AFD system in 2001 and 2011.

| AFD System | MMPS\textsubscript{2001} [m/s] | MMPS\textsubscript{2011} [m/s] | Annual Mean Change [%] |
|------------|------------------------------|------------------------------|------------------------|
| CI - T     | 12.24                        | 11.61                        | -0.51                  |
| SI - T     | 15.68                        | 15.01                        | -0.43                  |
| SI - NatA  | 15.81                        | 17.17                        | 0.86                   |

SI Figure 4 shows a correlation between vehicle mass and fuel consumption. Here, each 100 kg reduction in vehicle mass led to reduced fuel consumption by an mean 0.62 L/100 km in CI LDVs (orange diamonds) and 0.42 L/100 km in SI LDVs (green circles).

![Scatter of vehicle mass against fuel consumption for SI (green circles) and CI (orange diamonds) vehicles. The plot is based on the representation of all available vehicles, including high performance LDVs, where mass may influence the correlations. The exclusion of vehicles over 1,800 kg in mass reduces the coefficient of determination ($R^2$) to 0.6 for both SI and CI.](image-url)
Comparison of Performance using Normalised Relationships

Normalised engine design metrics are discussed to compare technological LDV advancements, independent of engine size. This includes an analysis of BMEP and specific power by AFD system from 2001 to 2011.

Maximum BMEP and mean piston speed are almost fixed for particular AFD system. Assuming equal bore and stroke lengths for engines of similar geometry \((B = L, \text{with } N_c = \text{Number of cylinders in Equation 5 (Heywood & Welling, 2009)})\), stroke length is eliminated from Equation 4 to yield the scaling relationship in Equation 6:

\[
V_d = N_c L \frac{2B^2}{4} \Rightarrow L^3 = \frac{4V_d}{N_c \pi} \quad \text{(SI 3)}
\]

\[
P_{b,\text{max}} = 0.27 \cdot BMEP_{p,\text{max}} \cdot \bar{S}_{p,\text{max}} \cdot V_d^{2/3} \cdot N_c^{1/3} \quad \text{(SI 4)}
\]

Vehicle performance trends were reviewed for the most popular configurations of AFD system across model year. The assumptions of linear trends were assumed valid as \(R^2\) estimates exceeded 0.96 for all AFD configurations. SI Table 3 shows that relationships for NatA LDVs have the highest concurrence whilst the relationships for turbocharged LDVs have lowest. This reflects engine designers’ capacity to utilise boosted systems to simultaneously increase performance and reduce engine displacements.

Engine displacement was plotted against maximum power (SI Figure 5-A) and torque (SI Figure 5-B) to represent power density and BMEP at maximum torque. The gradients indicate that power density is highest for SI-T DI vehicles at 71 kW/l and validates the use of scaling relationships when quantifying LDV performance. For example, it is reasonable to expect engine designers to use SI-T DI engines when designing high-performance LDVs (Heywood & Welling, 2009), and for these vehicles to have highest estimates of power. Moreover, the gradients (see SI Table 3) in SI Figure 5-C show mean BMEP at maximum torque is highest for the CI over the comparable SI, DI over the comparable II and boosted over the comparable un-boosted engine. Differences between BMEP at maximum torque and power are attributed to frictional losses. Larger deviations occurred in CI vehicles, where friction is higher because larger engine sizes are required to accommodate higher compression ratios (Heywood, 1988, Gupta, 2006).

Two further correlations are plotted in SI Figure 6 based on SI Equations 3 and 4. The first relates engine power, size and cylinder numbers to the inverse of BMEP which showed the largest variability of all the scaling relationships presented. Variability is lowest for the relationship between acceleration time and mass-to-power ratios at \(R^2 \geq 0.98\) for all systems. Here, deviations between the slopes (which represent the inverse of mean velocity) are attributed to differences between mean AFD-system velocities and the higher mass-to-power ratios of CI over SI vehicles.
SI Table 3: Normalised UK vehicle performance by AFD system. Slope of PFI converted to percentage.

| Performance Metric (Scaling Relationship) | AFD System | Sample Size | R²  | Slope   |
|------------------------------------------|------------|-------------|-----|---------|
| Power density (Max. Power Vs. Engine Size) | CI-T, DI   | 425         | 0.97| 48.2 kW/l |
|                                           | SI-T, DI   | 59          | 0.97| 70.7 kW/l |
|                                           | SI-NatA, DI | 66         | 0.98| 58.2 kW/l |
|                                           | SI-NatA, II | 836       | 0.97| 55.6 kW/l |
| BMEP at Max. Torque (Max. Torque Vs. Engine Size) | CI-T, DI | 358         | 0.97| 1,820 kPa |
|                                           | SI-T, DI   | 54          | 0.97| 1,660 kPa |
|                                           | SI-NatA, DI | 55        | 0.99| 1,290 kPa |
|                                           | SI-NatA, II | 750       | 0.99| 1,220 kPa |
| BMEP at Max. Power (Normalised Power Vs. Piston Area) | CI-T, DI | 544         | 0.96| 1,550 kPa |
|                                           | SI-T, DI   | 72          | 0.98| 1,620 kPa |
|                                           | SI-NatA, DI | 69       | 0.99| 1,130 kPa |
|                                           | SI-NatA, II | 998      | 0.98| 1,100 kPa |
| Annual Rate of Technological Improvement (PFI) | CI-T, DI | 7,245       | 0.99| 6.2%    |
|                                           | SI-T, DI   | 831         | 0.97| 6.8%    |
|                                           | SI-NatA, DI | 738     | 0.99| 5.2%    |
|                                           | SI-NatA, II | 9,477    | 0.99| 4.8%    |
SI Figure 5: Scaling relationships for (A) maximum power versus engine displacement, (B) maximum torque versus engine displacement and (C) brake power and mean piston speed versus total piston area.
SI Figure 6: Scaling relationships for (A) Maximum power against engine size and the number of cylinders and (B) Mass-to-power ratio against acceleration time. Shaded areas represent the 95% confidence interval about the mean and slopes represented with m.