The Influence of Road Grade on Carbon Dioxide Emission for a Hybrid Bus under Real-World Urban and Extra Urban Driving Conditions.

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Abstract

Road grade is known to have a significant impact on vehicle fuel consumption and resultant Carbon Dioxide (CO_2) emission, due to its effect on engine power demand. The purpose of this paper is to investigate the CO_2 emission of a hybrid bus when driven over a range of road gradients under real-world driving conditions.

The Portable Emission Measurement System (PEMS) data utilised in this study were collected by the Institute for Internal Combustion Engines and Thermodynamics at the Graz University of Technology (TUG). The collected data comprise GPS, engine, battery and exhaust emission measurements recorded (at 1 Hz resolution) during three days of testing in the summer of 2011, over three bus routes in Graz, under a range of driving styles. The test vehicle was a Volvo 7700H parallel hybrid diesel-electric bus, which is propelled by the combination of a 4-cylinder 4.76-litre diesel engine producing 216 bhp and a 94 bhp (continuous) electric motor.

From these data, Vehicle Specific Power (VSP) was calculated to provide an estimate of the instantaneous propulsive power demand for each second of the bus' transit through the test routes. VSP was determined at each recorded data point from the vehicles' speed and the road grade, and includes the rolling resistance, the air drag, the gradient force and the acceleration force.

The recorded GPS altitude data were found to be inadequate for calculating road grade as there were significant elevation measurement errors caused by the loss of GPS signal during transit e.g. due to high buildings or trees. For this reason, a macro was devised in Excel to map each of the test data GPS points to the nearest point on an 'accurate elevation profile' derived from a data set of known elevation values at coordinates along the route. This provided an accurate method for calculating road grade.

This study quantifies the CO_2 emission of the hybrid bus at a variety of road grades and under a range of driving styles and demonstrates the relationship between VSP and CO_2 emission. Micro-analysis of a number of sections of varying gradient was conducted, investigating the VSP distribution of different driving styles, the propulsive power output from the diesel engine and electric motor and the effect on CO_2 emission and energy generation from braking. This analysis confirms that despite many other influencing factors, road grade has a clear and very significant influence on the hybrid bus CO_2 emission.

Under a range of driving modes, it has been shown that road grade has significant influence on the propulsive power demand of the vehicle, the percentage contribution from the diesel and electric power sources, and the recovery of braking energy.

The analysis suggests that an accurate road grade profile is essential for the microscale modelling of hybrid bus emissions. Such modelling could be utilised to inform eco-driver bus training or used to define algorithms for the hybrid bus' Powertrain Management Unit (PMU) which could lead to improved management of the diesel engine and electric motor to minimise CO_2 emission over specified routes.

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Introduction

A number of studies have highlighted the importance of road grade on the fuel consumption and vehicle exhaust emission of diesel and petrol powered vehicles (Boriboonsomsin and Barth, 2009; Frey et al., 2008). When a vehicle is driven uphill, as the positive road grade increases so does the force due to gravity opposing the motion of the vehicle. Thus as the gradient of the road increases so does the propulsive engine power demand required to keep the vehicle at a constant speed or to accelerate it. This requires greater fuel consumption, which results in greater CO_2 emission.

For a hybrid vehicle however the relationship between road grade and CO_2 emission is not quite as simple, since the addition of the electric motor provides a source of propulsive power free of CO_2 emission. Very limited real-world data have published for hybrid bus operation. The work reported in this paper utilises data recorded in real-world driving conditions to quantify the relationship between road grade and CO_2 emission for a hybrid bus, and to investigate other factors related to the operation of an electric motor in combination with a diesel engine.

Methodology

Test Vehicle. A Volvo 7700H parallel hybrid diesel-electric bus was used as the test vehicle in this research. The parallel hybrid system combines a 4-cylinder 4.76-litre diesel engine producing 216 bhp with an electric motor that has a power output of 94 bhp (continuous). The hybrid bus can operate in the range from fully electric to fully diesel power, with the engagement and disengagement of the power sources controlled by a PMU which optimises their deployment whilst maintaining battery charge. The bus battery is recharged during transit through both a regenerative braking system where the electric motor acts as a generator under braking and at higher speeds by using overspill power from the diesel engine to run the motor in generator mode.

Study Design. Three bus routes in Graz were used as test cycles for the research. These were: route 31 a relatively flat 'inner-city' route 19.9 km long; Route 53 an 'out-of-town' route 25.2 km in length; and Route 60, an 8.4 km route with a significant hill. Each test route was driven four times with the PEMS setup, by the same driver, under specified driving modes which differed by the applied aggressiveness of acceleration and braking. The range of driving modes was 'aggressive' (mode A), 'normal' (mode N), 'passive' (mode P) and 'passive – only stopping at every other bus stop' (mode P2S). Uncontrollable factors which affected fuel consumption during the test data collection include the ambient conditions (which influenced the power demand of the bus' A/C system) and different traffic situations encountered on each test run.

Test Vehicle Instrumentation. The TUG design utilised a number of instruments which logged data at a rate of 1Hz. GPS data were recorded by a Race Logic VBOX; measurement of the battery parameters including the battery State of Charge (SOC) and electrical charging and discharging was recorded on a battery logger from Magna E-Car Systems; CANalyzer data was provided for the bus' systems; and emission measurements were recorded by a Semtech-DS Portable Emissions Measurement System.

Route Elevation. The recorded GPS altitude data were found to be inadequate for calculating road grade as there were significant elevation measurement errors caused by the loss of GPS signal during transit e.g. due to high buildings or trees. In order to add an accurate elevation to each of the test data GPS points a worksheet in Excel was constructed which geometrically mapped each of the test GPS points to a corresponding point on an accurate altitude profile.

The accurate elevation profile was provided from survey work undertaken by the Graz land surveying office along each of the test bus routes, and constituted a database of GPS points with verified altitudes. There were a total of 357 points over 12.6 km for line 53, 180 points over 4.2km for line 60, and 319 points over 9.7 km for line 31.

Vehicle Specific Power (VSP). VSP was calculated using a modified version of the standard VSP equation (Jimenez, 1999) reflecting the rolling resistance term coefficient (0.092) and aerodynamic drag term coefficient (0.00021) of a diesel transit bus (Zhai et al., 2008): where the rolling resistance term coefficient is the rolling resistance coefficient of the bus multiplied by the acceleration due to gravity ($F_0 / m_{bus} = m_{bus} * RRC * g / m_{bus} = RRC * g$), and the drag term coefficient is half of the aerodynamic drag coefficient of the vehicle multiplied by the frontal area

of the vehicle and the ambient air density divided by the mass of the bus (F_2 / m_{bus} = 0.5 * C_d * A_{cr} * ρ_{air} / m_{bus}). For the purpose of this study the coefficients were assumed to be the same for hybrid-diesel bus as those of the diesel transit bus.

$$\mathbf{VSP_{bus}} = v \cdot (a + 9.81 \cdot \sin(\text{grade}) + 0.092) + 0.00021 \cdot v^3$$

Where **VSP** is vehicle specific power (kW/tonne); **v** is vehicle speed (m/s); **a** is vehicle acceleration (m/s^2); **grade** is road grade (dimensionless)

Results and Discussion

Road Grade and CO_2 Emission. Each of the three test cycles (Graz bus routes 31, 53 and 60) was completed four times under specified driving modes. These test cycles were then divided into shorter test cycle sections to aid analysis. Figure 1, which plots the section mass CO_2 emission in g/km against the average road grade for each of the test sections, reveals a clear positive relationship between road grade and the hybrid bus' level of CO_2 emission.

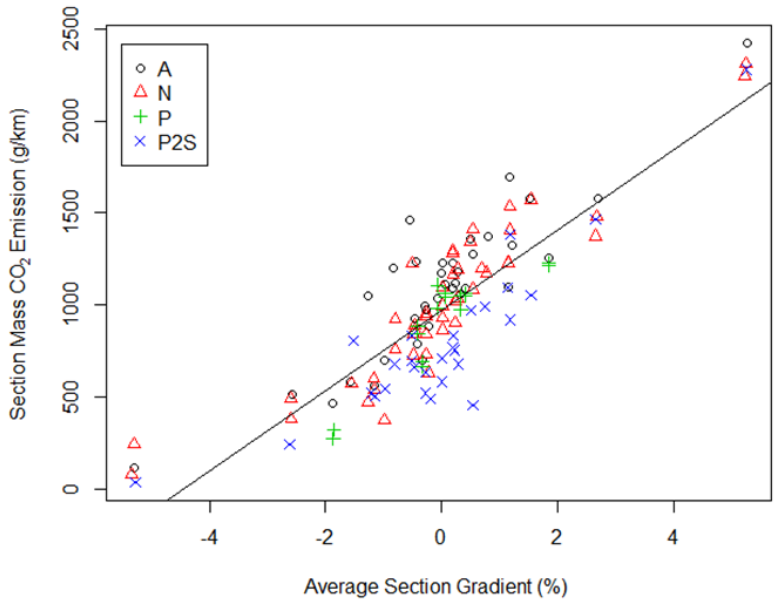


Figure 1. Test Route Sections: Average CO_2 Emission vs. Average Section Gradient

As would be expected, the uphill sections are shown to have the highest emission and the downhill the lowest. The average measured emission of CO_2 for the hybrid bus, on a flat road section, was around 1000 g/km, which corresponds to fuel consumption of approximately 38 litres of diesel per 100 km. It is also clear from Figure 1 that driving mode has a significant impact on CO_2 emission, with 'aggressive' driving commonly generating the largest amount of CO_2 emission at each road grade and 'passive' driving the lowest.

VSP and CO_2 Emission. Second-by-second analysis of VSP and CO_2 emission yields results that concur with the work of previous studies (Coelho et al., 2009; Song and Yu, 2009; Zhai et al., 2008) in revealing a monotonic increase in CO_2 emission with positive VSP and a consistently low CO_2 emission rate with negative VSP. For example, Figure 2 shows the average CO_2 emission of the bus at each VSP, for the test cycle Route 53, conducted in the 'P' driving mode.

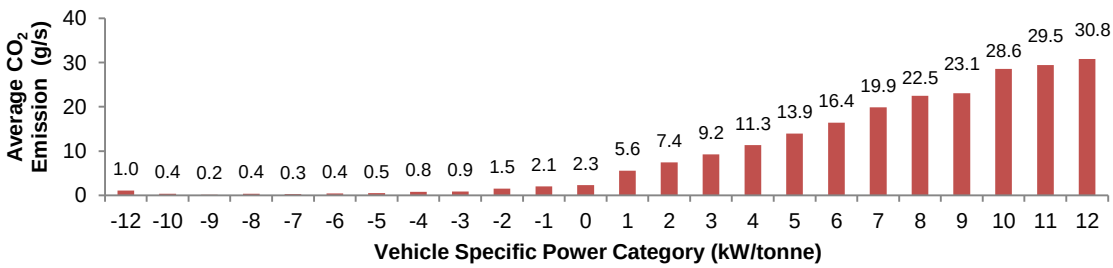


Figure 2. Passive Driving Mode Route 53: VSP (kW/tonne) vs. CO_2 Emission Rate (g/s)

Large VSP values describe points on the test cycle where substantial propulsive power was supplied, e.g. times of hard acceleration. At these points large amounts of fuel were combusted to produce the required power, resulting in a high rate of CO_2 emission. VSP values of less than zero indicate points where the vehicle is braking. CO_2 emission will be low when the vehicle brakes because the throttle pedal is disengaged. The CO_2 emission during negative VSP results from inevitable slight inaccuracies in the second-by-second gradient force calculation, especially for the coasting vehicle.

Micro-Analysis. To investigate the effect of road grade and driving mode on charging and discharging of the vehicle's battery and CO_2 emission more closely, eight test sections were selected representing a range of road grades (from ± 0.15 % to ± 3 %) and the range of driving styles (A, N, P and P2S). For each test section the outgoing and return journey on the same stretch of road were recorded, so each section has uphill and downhill measurements.

Three sections of road from the test cycles were selected to describe 'flat', 'intermediate' and 'steep' road grade. The first road section, 4.3 km in length with a relatively flat average gradient of ± 0.15 %, was analysed in three different driving modes ('A', 'N' and 'P2S'). The second, measured over a 4.4 km distance with an average road grade of ± 1.85 % was analysed under two driving modes ('A' and 'P'), and the third over 3.5 km with a steeper average road grade of ± 3 % was analysed with driving modes 'A', 'N' and 'P2S'.

VSP and Driving Mode. Figure 3 plots the VSP frequency distributions for each of the driving modes over the flat (± 0.15 %) road section (excluding VSP values of zero, where the bus was standing or coasting). For the section driven in the 'P2S' mode the majority of VSP values for the moving vehicle are between -2 and +3 kW/tonne, indicating soft acceleration and braking. In comparison the VSP frequency distribution of the 'A' driving mode is much more uniform over a greater range of VSP values, highlighting the hard acceleration and braking employed in this driving style. 40 % of the VSP values in mode A were greater than 4 kW/tonne compared with 12 % in mode P2S. From the relationship of VSP and CO_2 emission shown in Figure 2, it is clear that the aggressive driving mode has resulted in far greater emission than the passive mode for this test section.

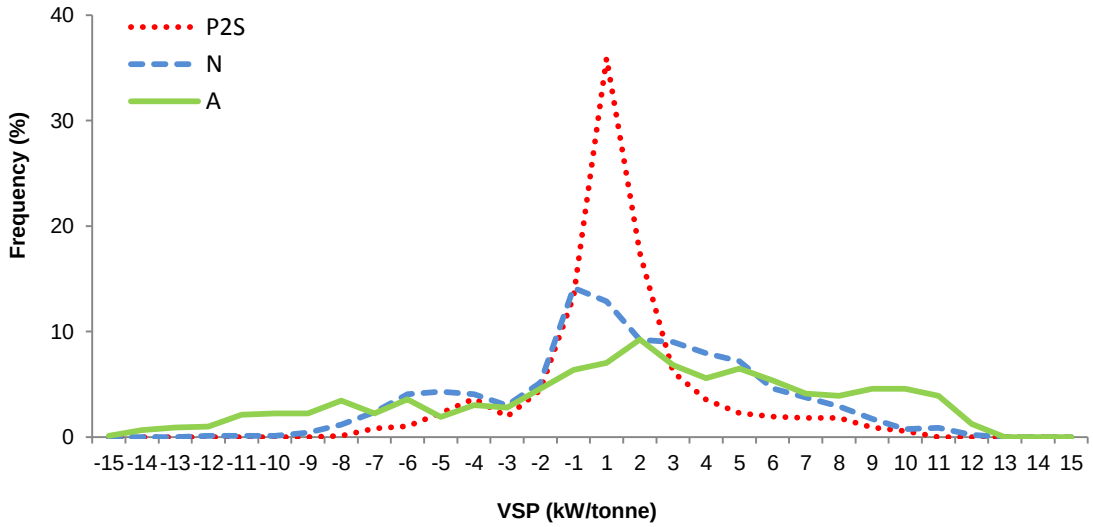


Figure 3. VSP Frequency for Each Driving Mode in the Flat (±0.15%) Test Section

For the steep (± 3 %) test section there was much less disparity between the VSP frequency distributions in each of the driving modes. Figure 4 shows that each driving mode had a very similar frequency distribution. This is due to a number of factors. Whilst travelling on the steep section, the bus averaged 1.4 stops per km compared with 2.1 stops per km in the flat section. This means that there were fewer acceleration and deceleration events to differentiate the driving mode. Furthermore, the steep road grade also had a homogenising influence on the driving modes, because more frequent use of full throttle was necessary to overcome the increased opposing force in uphill sections and a corresponding lower use of the throttle was necessary on downhill sections. Consequently the influence of driving mode on CO_2 emission was much more limited for this steep section, with only an 11 % rise in emission between mode P2S and A (N.B. for the flat section this increase was 73 %).

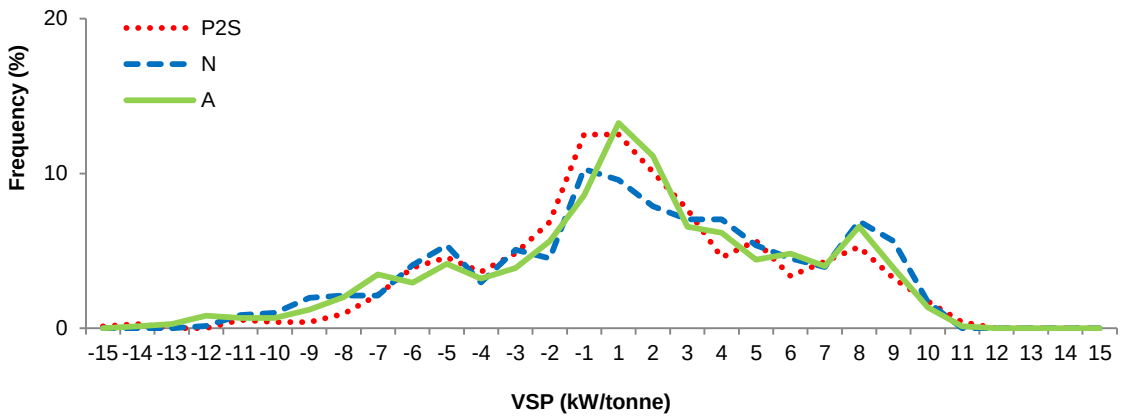


Figure 4. VSP Frequency for Each Driving Mode in the Steep (±3%) Test Section

Diesel Engine and Electric Motor Energy Output and CO_2 emission. Figure 5 shows the total energy output per km to propel the vehicle in each section and the approximate percentage contribution from the diesel engine and electric motor to this output. The sections are divided into their uphill and downhill segments and the mass CO_2 emission per km for each segment is given.

The energy output supplied to propel the vehicle (acceleration work) in each test section was calculated by multiplying the VSP at each data point by the weight of the bus (13 tonnes) to give the instantaneous power, in kW, for each second. All positive power values in a test section were then summed to estimate the total propulsive energy output, which was divided by the test section length to give the energy output per km.

The electric motor's contribution to the accelerating work was estimated by comparing the total propulsion energy output to the energy output from the battery (the sum of the electric discharging values). However, it should be noted that the calculated propulsive energy output from the electric motor is an overestimate of the real value, as it includes a percentage of the output from the battery which was not applied in propulsion but used to power auxiliary components such as the air conditioning, air compressor and power steering. Unfortunately a detailed breakdown of electrical power flows to all components during the bus' operation was not possible in this analysis, because only the battery power was measured during testing.

Figure 5 shows the large influence driving style and road grade have on the CO_2 emission of the hybrid bus. Over the flat section, on which the greatest disparity was found between the VSP distribution of each driving mode, the average energy output rises with increased aggressiveness in driving style, from an average of 2.22 MJ/km for mode P2S to 4.60 MJ/km for mode A. The output from the electric motor also increases with driving aggressiveness, from an average of 0.83 MJ/km for mode P2S to 1.87 MJ/km for mode A. However, the percentage contribution from the electric motor to the total energy output increases only slightly with driving style for uphill sections (from 32 % for P2S to 38 % for A) and is almost identical for each of the downhill sections (42 % for PS2 to 43 % for A). The results indicate that in the flat section aggressive driving requires greater power output from the diesel engine which results in greater fuel consumption and increased CO_2 emission.

For the steeper road section, despite similar VSP distributions for each driving mode, the downhill segments show the same pattern of increased CO_2 emission with increased aggressiveness of driving style, from 269 gCO_2/km for mode P2S to 399 gCO_2/km in mode A. The uphill segments, however, have a very similar average energy output, with 5.61, 5.64 and 5.4 MJ/km for modes P2S, N and A, respectively. As the energy output from the electric motor is between 19 % and 20 % for each of these test runs, the average energy output from the diesel engine is therefore approximately the same for each mode, resulting in broadly similar rates of CO_2 emission. This is highlighted in Table 1, which presents the average CO_2 emission for the most aggressive (mode A) and the most passive (mode PS2) driving styles on the flat section and the steep road section, and compares the emission in those modes to the emission from the normal driving mode. This shows that the CO_2 emission rate on the steep uphill segment driven in mode A is only 5% greater than the same segment in driven in mode N, whilst the emission in mode P2S for this segment was only 3% lower than mode N.

Table 1: Road Segment CO_2 Emission by Driving Mode and Road Grade and Comparison to Normal Driving Mode CO_2 Emission for each Segment.

Driving mode	P2S	P2S	A	A	P2S	P2S	A	A
Road grade (%)	+0.15	- 0.15	+0.15	- 0.15	+ 3	- 3	+ 3	- 3
CO_2 emission (gCO_2/km)	637	667	1200	1057	1596	269	1676	399
Difference in CO_2 emission between driving mode and driving mode N (%)	- 34	- 29	+ 88	+ 58	- 3	- 26	+ 5	+ 48

Figure 5 also highlights the stark difference in energy output and CO_2 emission between steep uphill and steep downhill sections. The percentage contribution from the electric motor varies considerably with road grade with a majority of the propulsive power in downhill sections provided by the electric motor and uphill sections mainly being driven utilising the power of the diesel engine. The uphill sections require 5.55 MJ/km (averaged across each of the driving modes), with approximately 20 % of the power provided by the electric motor, and the downhill sections require 1.52 MJ/km with an average 65 % of the power provided by the electric motor.

Although other exhaust pollutants are not included in this study and their emission is heavily dependent on the exhaust after-treatment systems, it is worth noting that possible benefits to local air quality through the introduction of hybrid buses are unlikely to be uniform over any bus routes where there are significant changes of road grade. Downhill and flat sections of road show significantly reduced fuel consumption (and therefore potentially emission) for the hybrid bus, in comparison to standard diesel buses, since the electric motor is a significant contributor to propulsive power in these sections. However, on steep uphill sections (where the results indicate a lower percentage contribution from the electric motor) the downsized diesel engine in the hybrid bus will be required to generate a majority of the time at a high propulsive power, and this strain on a smaller less powerful engine could increase the emission of pollutants such as Nitrogen Oxides (NOx). This is an area for future investigation.

Energy Generation from Braking. The Volvo 7700H has a regenerative braking system that captures energy generated when the vehicle's brakes are applied and converts it into electricity to recharge the bus' battery. Figure 6 presents the percentage of braking energy recuperated for each of the 8 test sections, in their uphill and downhill runs.

The total energy in each test section which could potentially be recovered by the hybrid bus has been derived by a similar methodology to that used to calculate the acceleration work, but rather than summing all positive power values, the negative power values have been summed to provide an estimate of the total braking energy for each test section. The recovered brake energy for each section has been calculated by adding the electric charging power values for every second that both the battery was charging and the vehicle was braking i.e. when the VSP was less than zero. At higher speed, the battery on the hybrid bus can also be recharged by the diesel engine effectively driving the electric motor as a generator. For this reason all points of battery charging at positive VSP values were identified and excluded.

Figure 6 shows that both road grade and driving style have a significant impact on the amount of braking energy generated and the percentage of the braking energy captured. The results suggest that during aggressive braking, the mechanical and electrical braking power is higher than in the passive case. However, the percentage recovery decreases with more aggressive braking, because the electrical braking power generation of the hybrid bus is limited to approximately 90 kW.

For the flat test section, the disparity between the uphill and downhill sections appears to be the result of the different numbers of stops on the test runs through each section, highlighting that, for sections with fewer stops there is less braking energy available to charge the battery. For the sections with steeper gradient, the disparity between uphill and downhill appears to be caused by the influence of the road grade, with less braking required on uphill sections (as the force of gravity acts to slow the motion of the vehicle) and harder braking necessary on downhill sections (where gravity acts to accelerate the vehicle).

Figure 5: Energy output per kilometre for the diesel engine and electric motor of the hybrid bus, through test sections defined by road grade and driving style, with the percentage of the energy output from the electric motor and CO_2 emission per km for each test section

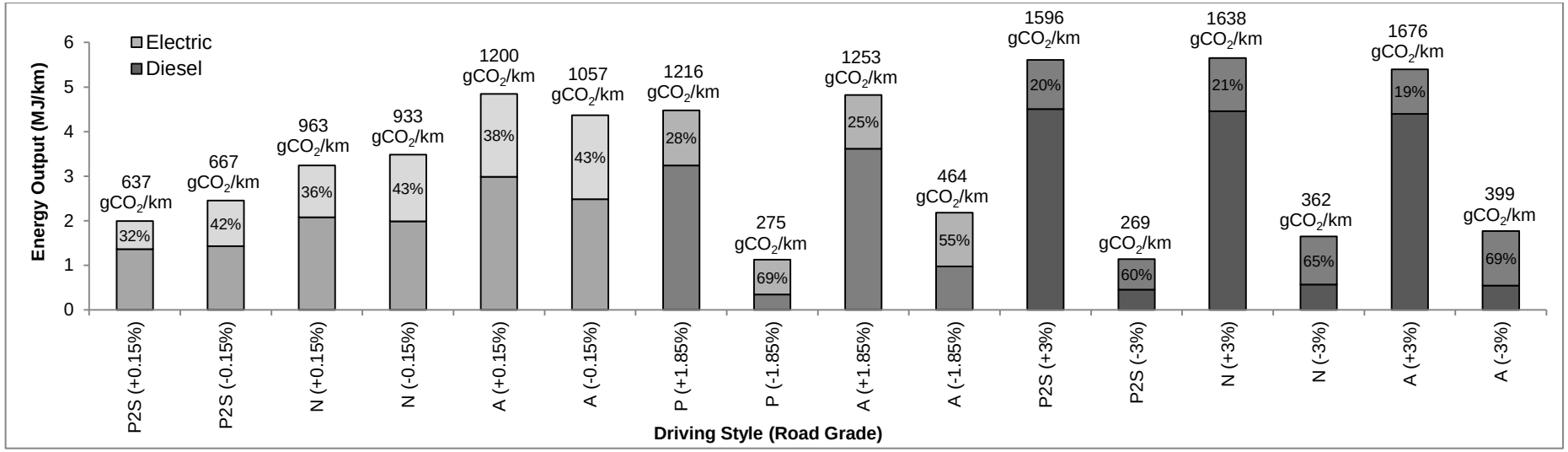
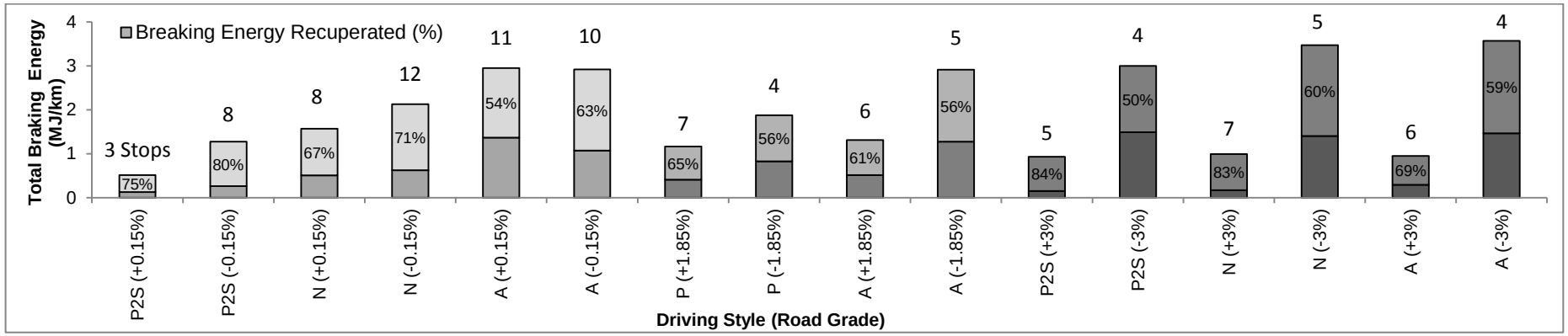


Figure 6: Percentage of total braking energy recuperated by the hybrid bus during braking for each test section defined by road grade and driving style (the number of stops in each test section is reported above the bars)



Conclusion

The work reported in this paper provides some quantification of the important role that road grade plays in influencing hybrid bus CO_2 emission. Road grade, under a range of driving modes, has been shown to have significant influence on the propulsive power demand of the vehicle, the percentage contribution from the diesel and electric power sources, and the recovery of braking energy.

The analysis suggests that an accurate road grade profile is essential for the microscale modelling of hybrid bus emissions. Such modelling could be utilised to inform eco-driver bus training or used to define algorithms for the hybrid bus' PMU which could lead to improved management of the diesel engine and electric motor to minimise CO_2 emission over specified bus routes.

References

Boriboonsomsin, K. and M. Barth (2009), Impacts of Road Grade on Fuel Consumption and Carbon Dioxide Emissions Evidenced by Use of Advanced Navigation Systems. *Transportation Research Record.* (2139): p.44-53

Coelho, M.C., Frey, C.H., Rouphail, N.M., Zhai, H. and L. Pelkmans (2009), Assessing methods for comparing emissions from gasoline and diesel light-duty vehicles based on microscale measurements. *Transportation Research Part D-Transport and Environment*, 14(2): p. 91-99.

Jimenez-Palacios, J. (1999), Understanding and quantifying motor vehicle emissions with vehicle specific power and TILDAS remote sensing. Doctoral Dissertation, Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA.

Frey, H.C., Zhang, K.S. and N.M. Rouphail (2008), Fuel use and emissions comparisons for alternative routes, time of day, road grade, and vehicles based on in-use measurements. *Environmental Science & Technology.* 42(7): p.2483-2489.

Song, G.H. and L. Yu (2009), Estimation of Fuel Efficiency of Road Traffic by Characterization of Vehicle-Specific Power and Speed Based on Floating Car Data. *Transportation Research Record*, (2139): p. 11-20.

Zhai, H.B., H.C. Frey, and N.M. Rouphail (2008), A Vehicle-Specific Power Approach to Speed- and Facility-Specific Emissions Estimates for Diesel Transit Buses. *Environmental Science & Technology*, 42(21): p. 7985-7991