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Independent, not-for-profit, low emission vehicle and energy for transport experts

Final Project Report

Havana Technology Foresighting

A review of low emission vehicle technology and infrastructure for the Havana public transport system

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**Table of Abbreviations**

|  |  |
| --- | --- |
| BEV | Battery electric vehicle |
| CO2e | Carbon dioxide equivalent |
| COPERT | A software tool used to calculate emissions from road transport |
| DPF | Diesel particulate filters |
| DPF | Diesel Particule Filter |
| ECSA | Electrochemically active surface area |
| EU | European Union |
| EV | Electric vehicle |
| FCEV | Fuel cell electric vehicle |
| GHG | Greenhouse Gas |
| GWP | Global Warming Potential |
| H2FC | Hydrogen Fuel Cell |
| HDS | Hydrogen de-sulfurization |
| HEV | Hybrid electric vehicle |
| HGV | Heavy Goods Vehicles |
| ICE | Internal combustion engine |
| IPCC | Intergovernmental Panel on Climate Change |
| kW | Kilowatt |
| kWh | Kilowatt-hours |
| kWp | Kilowatts at peak solar irradiance |
| MPA | Miles per annum |
| NEDC | New European driving cycle |
| NOx | Oxides of nitrogen |
| NPV | Net present value |
| ODS | Oxygen-based desulphurisation |
| OJEU | Official Journal of the European Union |
| OPP | Outright purchase price |
| PHEV | Plug in hybrid vehicle |
| PM | Particulate matter |
| PPM | Parts per million |
| PTAL | Public transport accessibility levels |
| REEV | Range extended electric vehicle |
| RET | Renewable energy technology |
| ROI | Return on Investment |
| RPM | Revolutions per Minute |
| SCR | Selective catalytic reduction |
| SO2 | Sulphur Dioxide |
| TCO | Total cost of ownership |
| TTW | Tank to Wheel |
| ULEV | Ultra Low Emission Vehicle |
| US | United States |
| WTW | Well to Wheel |

# Executive Summary

**Scope of this report**. This foresighting report was prepared for Havana’s transport authority as it seeks to reduce fuel and operational costs by adopting more fuel-efficient, cleaner vehicles. It outlines the relative benefits for the Havana transport authority of adopting alternative modern powertrain[[1]](#footnote-1) technologies, in terms of emissions and total costs of ownership.

**Not included in this report**. This report does not include a detailed analysis of capital expenditure, operating expenditure, investments guidance, or the costs of anti-corruption supervision, alternative sources of funding or training for ongoing maintenance and repair. This more detailed work would need to be carried out prior to any procurement decisions being made.

## Suitability of low emission technologies

**Updated vehicle technologies** would provide a range of environmental and economic benefits, including reduced emissions of particulate matter (PM), nitrous oxides (NOX), and carbon dioxide (CO2e), as well as reduced fuel and total cost of ownership of vehicles. In updating their fleet, transport authorities have to choose between:

* **Lower emission conventional vehicles**, such as EU VI diesel powertrains. These technologies are available already, but the introduction of lower emission vehicles would require improvements in the refinery level desulphurisation process to ensure the reduction of sulphur-based compounds to 15 parts per million (PPM) or less.
  + It is estimated that the gradual introduction of improved diesel engines within the Havana bus fleet, based on achieving an EU VI emission profile over 10 years, could potentially displace 28,000 tonnes of Well-to-Wheel CO2e per year and improve air quality by reducing NOX emissions by 376,000 kg and PM emissions by 19,000 kg. Fuel savings of up to 25% could also be achieved and emissions reduced by: up to 19% for well-to-wheel and tank-to-wheel CO2e; up to 93% for tailpipe NOx; and 98% for tailpipe PM.
* **Alternative powertrains: hybrids vs electric vehicles**. There are a number of relevant low carbon powertrain technologies already available, with further improvements under development. However, the high sulphur content of Cuban diesel fuel will negatively impact the operation of such vehicles. Therefore, Havana might want to consider an accelerated adoption of electric vehicles. This would necessitate the reinforcement of the local electricity grid through the installation of dedicated charging points and associated electricity substations.
* **Technology transition options**. Current policy has been adoption of hybrids in the shorter term, with a gradual transition to full electric as the grid is developed to cope. This approach is appropriate, as it allows for technological upgrading with less immediate burden on the grid.
* **Trams/ trolley bus systems**. The high costs of installation and maintenance of rails and associated overhead powerlines mean that such systems would be unlikely to be economically viable for most routes, although they could be considered for the longest, busiest routes.

## Outcomes

**Additional costs and benefits beyond the scope of this report**. The suitability of different types of low emission technology depends on a range of other factors, including additional infrastructure costs to provide adequate power supply, and short, medium and long-term storage of fuel/power. In addition, other potential benefits include reduced vehicle noise and the provision of power reserves and back-up power systems by battery electric or fuel cell vehicles in the event of an emergency or loss of power from the electricity grid.

**Suggestions for further analysis.** The relative benefits of alternative technologies depend on current and projected public transport usage, Cuba’s future renewables infrastructure, and relative costs within Cuba. A full investment appraisal would require a detailed assessment and full calculations of the cost and emissions implications of this technology transition.

# Introduction: Context

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| **Key Points** |
| **Methodology**  The information in this report is derived from desk-based research and Cenex expertise. With this information, Cenex modelling is used to generate an initial assessment of the suitability of a range of low emission technologies within the Havana bus fleet.  **Key findings: the contribution of this study in the Cuban context**   * **Policy**. In line with central government policy guidelines, principles and plans, Havana’s transport authority plans to make significant capital investments to replace its aged public transport fleet to make a transition to vehicles with lower emissions, fuel consumption and running costs, and improve air quality and thus public health. * **Investment decision-making**. In making these investments, Havana’s transport authority will have to choose between the variety of possible technologies that are available now, or are likely to be in the near future. |

## Background, methodology and scope of the study

This technology foresighting study, funded by the British Embassy in Havana, has been carried out by Cenex, the UK’s leading low emission transport consultancy and research organisation, with extensive experience in delivering low emission foresighting studies for public transport authorities.

The study aims to provide information on the main technological advances and future developments in low emission transport, and their suitability for Havana’s transport authority as it seeks to address the challenge of improving public transport and mitigating climate change. The main focus of the report is on alternative powertrain technologies that offer carbon reduction from city buses, although technologies relevant to trams and trolley buses are also discussed.

The study draws on technology information gathered from desk-based research, including published Cuban official data, academic, technical and policy literature, industry technology roadmaps, information provided by the UK Foreign Office, University College London and the Open University, combined with the expertise of, and models developed by, Cenex. The Cenex model’s results and analysis primarily focus on the likely performance of short to medium term solutions (less than 10 years), with a brief discussion of mid to long-term measures is also considered.

Detailed analyses of future demand for public transport vehicles and procurement practices are beyond the remit of the current exercise. Cenex has the capacity to provide such analyses, which would require substantial input from, and extensive collaboration with, Havana’s transport authority.

## The Cuban context: policy, energy and the economy

Cuban urban mobility policy prioritises public transport, but due to tight financial constraints facing the Cuban economy in general, the level of investment in Havana’s public transport system has been limited. As a result, the public transport system does not provide sufficient capacity to meet demand, most of the current vehicle fleet is old and fuel inefficient, and in need of replacement. The main national documents setting out national economic development priorities (known as the Lineamientos, Concepcualizacion and Plan 2030), all refer to the priority given to public transport, as well as registering the need to improve energy efficiency, protect the environment and prioritise public health. These messages are repeatedly echoed by senior government officials, for example Ricardo Cabrisas (Deputy President of the Council of Ministers and Executive Committee), called for renewed efforts to tackle inefficiency in all aspects of Cuba’s energy consumption and to modernise wherever possible.

The *Anuario Estadístico de Cuba*, published by Cuba’s national statistics office (Oficina Nacional de Estadísticas e Información, ONEI), provides data on Cuban energy consumption, production and trade. This information confirms that although Cuba produces some of its own crude oil, it is heavily dependent on imported oil, which represents a large burden for the economy as a whole.

The ONEI report shows that Cuba’s total domestic consumption of crude oil has risen over the past decade, increasing from 5 million tonnes in 2007 to 5.5 million tonnes in 2016 (the latest year for which a crude oil consumption figure is available) (ONEI 2017, table 10.9). The increase in consumption has coincided with falling domestic production, which peaked at 3.7 million tonnes - almost half of domestic consumption - in 2003. In 2016 (the latest year for which the figure is available), Cuban oil production was 2.6 million tonnes, or around one third of national consumption (ONEI 2017, table 10.4). Although Cuba remains less oil dependent than it was at the beginning of the crisis of the 1990s, when domestic production was just 0.5 million tonnes, the trend towards rising consumption and diminishing production means that the country is likely to become increasingly oil import dependent unless policy action is taken to switch to other energy sources.

Rising oil import dependency is not immediately apparent from oil trade data, which provide a picture that has been complicated over the past decade because of imports and exports related to new refinery activity. Until 2008, Cuba’s imported oil was almost all used for domestic consumption, but in that year, the completion of the Cienfuegos oil refinery resulted in a surge in oil import spending on the one hand, and at the same time a new flow of export earnings as most of the refined products were re-exported. Figure 1 shows the sudden rise in oil imports in 2008-09 (the blue line), followed by a period of stability in imports then an abrupt downturn in 2016-17 when activity at the Cienfuegos refinery was reduced in order to upgrade facilities. It also shows (in orange) earnings from exports of oil products from the Cienfuegos refinery. As the chart shows, much of the surge in oil imports between 2008 and 2014 was accounted for by processing for export.

*Figure 1. Cuban oil trade, 2000-2017*

*Source: ONEI, Anuario Estadistico de Cuba, (2004, 2008, 2012, 2017)*

The difference between spending on oil imports and revenue from exports of oil products is ‘net oil import spending’ (shown in grey): the estimated amount spent on imported oil for domestic consumption (that is, net of the exported oil products from the Cienfuegos refinery). Spending on these net imports of fuel has fluctuated in line with the trend in world oil prices, which rose from 2004 and were exceptionally high during the 2011-15 period, more than trebling the cost of oil imports for domestic consumption. Energy is a thus a critical issue for Cuba’s sustainable economic development. Not only does the burden of energy imports absorb more than US$2bn a year on average, or around 20% of all import capacity, but dependence on imported fuel also leaves the country’s economic fortunes highly exposed to supply interruptions and vulnerable to the volatility of the world market price for oil.[[2]](#footnote-2)

This persistent and increasing dependency on oil imports creates an economic necessity to reduce overall energy demand, and also to shift, where possible, from oil dependency to other sources of energy. Political upheaval in Venezuela, Cuba’s main supplier of oil for more than a decade, has highlighted this need, particularly in the context of tightening US sanctions aimed at blocking Cuba’s access to finance and energy imports. Moreover, in addition to the economic vulnerability created by oil import dependency, the Cuban authorities are also aware of the damage to human health arising from vehicle emissions, as evidenced by research carried out by the meteorological and epidemiological research institutes and, as active participants in the international climate change discussions, Cuban scientists and officials are supportive of the need for reductions in greenhouse gas (GHG) emissions (although Cuba is a very minor contributor to global emissions).

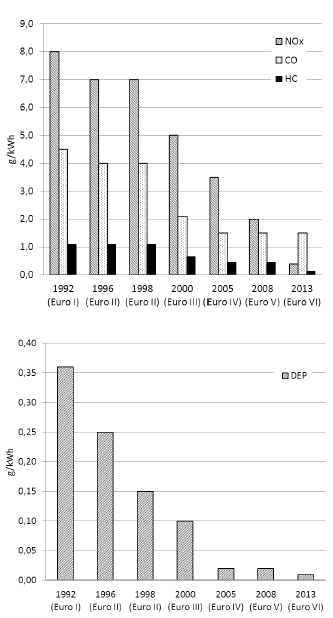
With the continuing improvement in vehicle fuel efficiency worldwide, combined with growing calls to step away from fossil fuels in many regions,[[3]](#footnote-3) Havana has the opportunity to consider the use of cleaner fuels, and to plan and implement policies for the transition to lower emission fuels and zero emission alternatives. However, with finance remaining severely restricted as a result of US sanctions, Cuba needs to give particularly careful consideration to deciding between the wide range of technologies available for such large investments, on the basis of their relative availability, costs and benefits.

# Global Trends & Baseline Havana Bus Fleet Emissions Estimate

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| **Key Points** |
| **Methodology**  A literature review examined the evolution of emissions standards globally to highlight the relative performance of Cuban buses. An estimate of current emissions from the Havana bus fleet is derived from the available information and a Cenex model based on UK usage patterns.  **Key Results**   * **Global context**. Worldwide trends are towards the adoption of ultra-low sulphur fuels in combination with urea and catalyst-based exhaust treatments to reduce harmful emissions. Considering EU emission standards, with Euro I representing the highest emissions to the Euro VI lowest emissions standard, in many markets Euro VI standards already dominate new vehicle purchases. * **Havana emissions baseline estimate**. Cuba is lagging behind global best practice, with emission standards for the existing fleet estimated at Euro I. Using Cenex’s model and available Cuban and international data, current emissions from Havana’s public transport system are:   + Well to wheel CO2e emissions: 146,109 tonnes per year   + Annual tailpipe emissions: CO2e 118,266 tonnes; NOX 406 tonnes; PM 19 tonnes.   **Next Steps**   * To more accurately model emissions from public transport vehicles in Havana, full information on the city’s specific bus duty cycles is needed. |

## Global context

As part of a worldwide effort to adopt cleaner fuel sources for heavy goods vehicles (HGVs) and buses emission standards for new vehicle engines have been tightened over the past 30 years. In the case of the European Union (EU), where standards are similar to other worldwide standards for emission monitoring and control, ever increasing improvements in emissions have been required since 1992, as shown in Figure 2.

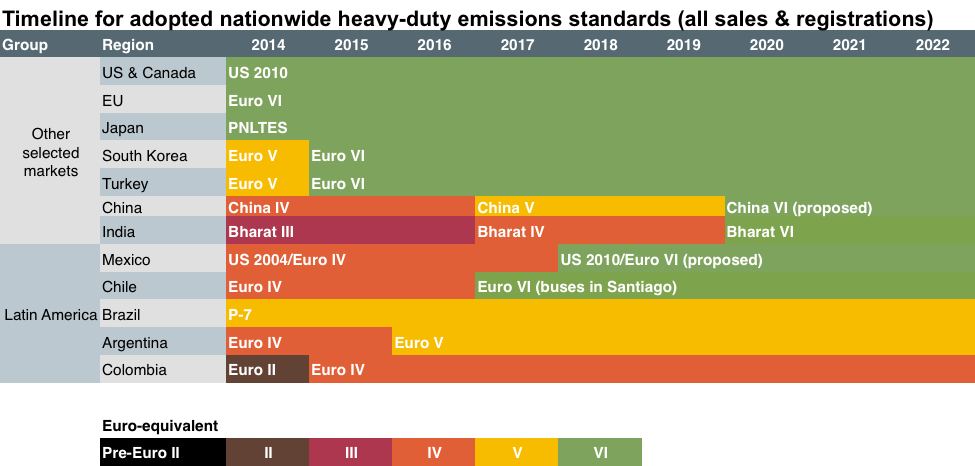
 *Figure 2: Emission standards for heavy duty diesel engines in the EU Euro I to VI*

*Source: Liu et.al. (2010).*

As shown in Figure 2, the emission standards are designated with Roman numerals (EU I to EU VI), with the most recent standard (EU VI) coming into force in 2013. The standard applies to both steady state operation - where the engine is operating at a constant speed (RPM), for example when cruising - and transient operations - where the engine is either accelerating or decelerating, before reaching a steady state. (Note that the main gain from the diesel-electric series hybrid is that the diesel motor runs at a ‘steady state’, that is, at a constant speed, and thus does not have all the inefficiencies and deficiencies associated with acceleration.) Manufacturers are also required to demonstrate the ability of the engine to continue to comply with the required emission limits over its useful life; this is known as emission durability.

Figure 3 shows the existing and planned emissions compliance for new vehicle sales in the larger Latin American economies, and also in other large markets, as reported in 2017. Note that in 2017, Chile became the only EU VI compliant country in Latin America, while the US, Canada, EU, Japan, South Korea, Turkey had all been compliant with this standard for at least two years. While Chile and Mexico have moved from EU IV to EU VI, Brazil and Argentina are expected to remain at EU V until after 2022, and Colombia is not expected to progress beyond EU IV by that date.

*Figure 3: Worldwide adoption of heavy-duty vehicle emission standards*



*Source: Façanha (2017)*

According to information provided to Cenex, the emissions profile of the existing bus fleet for Havana remains inferior to any of these countries, being broadly equivalent to the EU I emissions standard, which equates to vehicles registered in the early 1990s. This means that Havana are using an ageing bus fleet that operates on older, less fuel-efficient technologies, resulting in negative local and national environmental impacts.

Such local impacts include inner city air pollution through toxins such as nitrous oxides (NOx) and particulate matter (PM), which have serious impacts on the health and wellbeing of Havana’s population. Public transport vehicles’ emissions of CO2 and CO2 equivalent gases (CO2e), known as greenhouse gases (GHGs, which include NOx), also contribute to climate change. Although Cuba’s per capita contribution GHG emissions is lower than that of high income countries, and its overall contribution to global climate change is negligible, its government is in agreement with the UN Intergovernmental Panel on Climate Change (IPCC) in recognising the need for radical action to limit and, where possible, eliminate, anthropomorphic sources of CO2e.

## Havana bus fleet: total emissions baseline

To generate a baseline emissions estimate for the Havana bus fleet, Cenex assumed that the current emissions profile of the bus fleet was EU I. Operational assumptions, in terms of distance travelled, the driving pattern, fuel efficiency and the types of numbers of vehicles in the Havana bus fleet are set out in Tables 1 and 2. The assumptions used here are based on information supplied by the Open University.

*Table 1: Havana bus fleet operational assumptions*

|  |  |  |  |
| --- | --- | --- | --- |
|  | Distance travelled per year (km) | Duty cycle | Fuel efficiency (litres/ 100km) |
| Baseline (EU I) | 55,980 | Mostly congested | 101 |

*Source: Open University*

*Table 2: Baseline estimate for Havana bus fleet*

|  |  |
| --- | --- |
| Vehicle Type | Number of Vehicles |
| Articulated Bus | 226 |
| Standard Bus | 578 |
| Total | **804** |

*Source: Open University*

Based on the above fleet and operational data, Table 3 shows the Cenex modelled estimates for the total well-to-wheel and tank-to-wheel emissions for the Havana bus fleet. Note that the NOx and PM emissions are wholly generated by the vehicle, that is, tank-to-wheel.

*Table 3: Estimated current annual emissions from Havana bus fleet*

|  |  |
| --- | --- |
|  | Tonnes per annum |
| Well to Wheel CO2e emissions | 146,109 |
| Tank to Wheel CO2e emissions | 118,266 |
| NOx emissions | 406 |
| PM emissions | 19 |

The following section provides an overview of the technologies that have the potential to reduce the Havana bus fleet emissions from this baseline.

# Technology Review and Modelling

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| **Key Points** |
| **Methodology**  This section is based on a survey of the available information on low emission vehicle and infrastructure technologies that are currently available or in advanced stages of development.  **Key Results:**   * **Diesel engine emissions reduction systems.** Around the world, many public transport authorities have adopted low-emissions petrol or diesel-fuelled vehicles. Scenario modelling indicates that if EU VI engines are adopted throughout the Havana bus fleet, fuel savings of up to 25% could be achieved and emissions reduced by:   + up to 19% for well-to-wheel and tank-to-wheel CO2e   + up to 93% for tailpipe NOx   + up to 98% for tailpipe PM * **Alternative powertrains: electric and hydrogen fuel cell buses.** The use of battery electric (BEV) buses within urban areas is growing. Other technologies such as hydrogen fuel cell (H2FC) buses are in the research and demonstration phase with very few entering early commercial trials. Capital costs for such vehicles and infrastructure are higher than diesel but fuel costs for electric buses are lower and emissions savings greater.   + Actual costs and benefits depend on infrastructure needs and maintenance but are improving quickly as technology advances. * **Tram and trolley buses**. The emission profiles for both these types of vehicles are similar to that of electric buses. However, the infrastructure requirements are more expensive than electric buses due to the added cost for installing power lines and dedicated passenger platforms.   **Issues for consideration & next steps:**   * **Route mapping for electric vehicle infrastructure**. Detailed examination of routes would be needed to identify which routes would be most suitable in terms of sustaining additional infrastructure costs of electric vehicle infrastructure. * **Power constraints**. Careful consideration should also be given to the power requirements for an electrified bus system now and in the future. * **Interdependency of policy choices**. Havana must consider which technologies it can develop in isolation, and the wider future low emission technology introduction plans for Cuba. |

## Internal combustion engine emission reduction systems

Initial progress towards diesel emission control and reduction has been achieved through the use of engine technologies, including changes in the combustion chamber design, improved fuel systems, charge air cooling, and special attention to lubrication oil consumption. However, the implementation of tighter emission standards has required the availability of lower-sulphur fuel and additional use of exhaust after-treatment systems on new diesel engines. The use of alternative fuels also offers the potential for reduced emissions.

### Technologies for reducing emissions

#### Particulate filters

Diesel particulate filters (DPFs) are a physical filter that trap very fine particulate matter and prevents it escaping from the exhaust of the vehicle. Such filters require regular maintenance and the use of compatible oil and diesel. Well-maintained fitters can operate for 160,000 kilometres. Some filter designs include the ability to burn off the particulate matter and can partially regenerate themselves.

Diesel particulate filters can often be fitted to existing vehicles as a retrofit device at relatively low cost. However, the degree of maintenance required on retrofitted filter systems on older vehicles is far higher than those on new powertrain and exhaust systems.

#### Catalytic converters

Catalytic converters are high surface area devices coated with a catalyst material such as platinum, palladium, rhodium or aluminium. Catalyst converters are typically located one-third of the way along the length of the vehicle between the engine and the tailpipe. A catalytic converter substantially reduces the amount of harmful pollutants by taking these gases and converting them into water vapour and less harmful gases via a series of chemical reactions.

However, catalytic converters are very sensitive to certain chemicals such as sulphur, phosphorous and manganese. These poisoning agents bind onto the surface of the catalyst and prevent it from performing its normal reactions. Phosphorous is often found in certain grades of engine oil and as such low phosphor lubricants must be used to ensure catalyst efficiency is maintained.

Catalyst poisoning can, in some cases, be reversed through operation at high temperatures. However, such high-temperature operation must be very carefully controlled. At higher temperatures, smaller particles fuse to create larger particles which reduces the electrochemically active surface area (ECSA) of the catalyst. It is therefore essential to minimise unburnt hydrocarbons from entering the catalytic converter. If hydrocarbons combust inside the catalytic converter, runaway temperatures can cause irreversible damage to the ECSA of the catalyst.

#### Improved engine efficiency

Since the adoption of EU IV emission standards (2005), significant improvements in overall engine efficiency have been achieved. Adoption of the latest engine technologies, improved driver training and optimised maintenance regimes can reduce fuel use by up to 25%.

#### Reduced sulphur fuels

Sulphur compounds represent one of the most common impurities present in the crude oil, leading to the emission of sulphur dioxide (SO2) and sulphate particulate matter. Sulphur compounds can act as a poisoning agent for certain types of catalytic converter. Such poisoning events are often a reversible process if the correct temperature control can be achieved. However, it is unlikely that typical bus duty cycles can achieve the temperatures required to reverse sulphur based poisoning events. To overcome this, low sulphur fuels are required.

Typically, crude oil sulphur content is reported as between 30 parts per million (PPM) to 19,725 PPM. Many oil refineries and research laboratories are actively engaged in research and development projects to cost-effectively achieve levels of sulphur content below 10 PPM in their fuel products.

Crude oils with a high percentage of sulphur are more difficult to process and may require several different processes to remove. Two examples of desulphurisation techniques are:

* Hydrogen Desulphurisation (HDS). This requires relatively large amounts of high purity hydrogen, which can be made from natural gas through steam methane reforming or electrolysis of water. The process requires hydrogen gas at pressures of 3.0 to 5.0 megapascals (MPa), in the presence of catalysts such as cobalt-molybdenum (CoMo:AL2O3) or nickel-molybdenum (NiMo:AL2O3) at 300 to 450oC.
* Oxygen-based desulphurisation (ODS). This is a frequently used method, usually carried out in a two-stage process:
  + Autoxidation leads to the creation of hydroperoxides that can be removed through a water extraction process. Sulfoxides and sulfones can also be formed by controlled reactions with pure oxygen or through specific ionic solvents.
  + Such pure oxygen techniques combine well with electrolysed hydrogen production, as oxygen is also produced during the electrolytic process.
  + Oxidative desulphurisation can lead to significant increases in the viscosity of the crude if not properly controlled.

Full information on the sulphur content of Cuban oil was unavailable for the preparation of this report, however it is assumed that it will be approximately 5,000 PPM of sulphur after processing. This estimate is based on the sulphur content of similar fuels produced throughout Latin America.

#### Urea-based additives

Automotive grade urea, also known as diesel exhaust fluid and frequently traded under the name ‘AdBlue’, is a key component in selective catalytic reduction (SCR) systems. The urea acts as a reducing agent that reacts with NOX compounds to produce nitrogen, water and CO2. Typically, the urea additive is injected into the exhaust stream after the exhaust gases exit the particulate filter. In combination with the catalytic converter the NOX, unburnt hydrocarbons and carbon monoxide content of exhaust gases can be reduced by up to 90%. The system can also help reduce PM emission. Vehicles using SCR need to have a separate tank fitted to house the Urea and this needs to be topped up regularly (i.e. whenever refuelling the vehicle).

#### Alternative fuel engines

Emissions reductions can also be achieved by using vehicles with a modified internal combustion engine to run on alternative fuels. For alternative fuel engines, a range of different types of fuel have been developed which are summarised in Table 4.

***Table 4: Overview of alternative fuels***

|  |  |  |
| --- | --- | --- |
| Alternative Fuel Type | Description | Comments |
| High Blend Biofuels | Blends of fossil and biofuels higher than those allowed under the current diesel (EN590) and petrol (EN228) European standards. | The higher the blend of biofuel, the higher the potential emission reduction, depending on the source of the bio element. Costs depend on source and availability. |
| Drop-in Fuels | Biofuels that can be blended up to 100% with fossil fuels and maintain the current diesel (EN590) and petrol (EN228) European standards. | The development of drop-in fuels is still relatively new and may be cost prohibitive. |
| Pure Plant Oil (PPO) | A fuel based on 100% vegetable oil. | Potential for high emission reductions, depending on the source of the vegetable oil. Costs depend on source and availability. |
| Natural Gas | A fossil-based road transport fuel consisting of mainly methane. | Emissions similar to that of EU VI diesel. Costs depend on source and availability. |
| Biomethane | A sustainable (i.e. non-fossil-based) road transport fuel consisting of mainly methane. Biomethane is chemically similar and interchangeable with natural gas as a fuel. | Potential for high emission reductions, depending on the source of the biomethane. Costs depend on source and availability. |
| Hydrogen | Hydrogen can be used to power vehicles, either through direct combustion or a fuel cell. | Potential for high emission reductions, depending on the source of the hydrogen. Costs depend on manufacturing method and availability. |

### Scenario modelling for diesel engine emissions reduction

#### Method

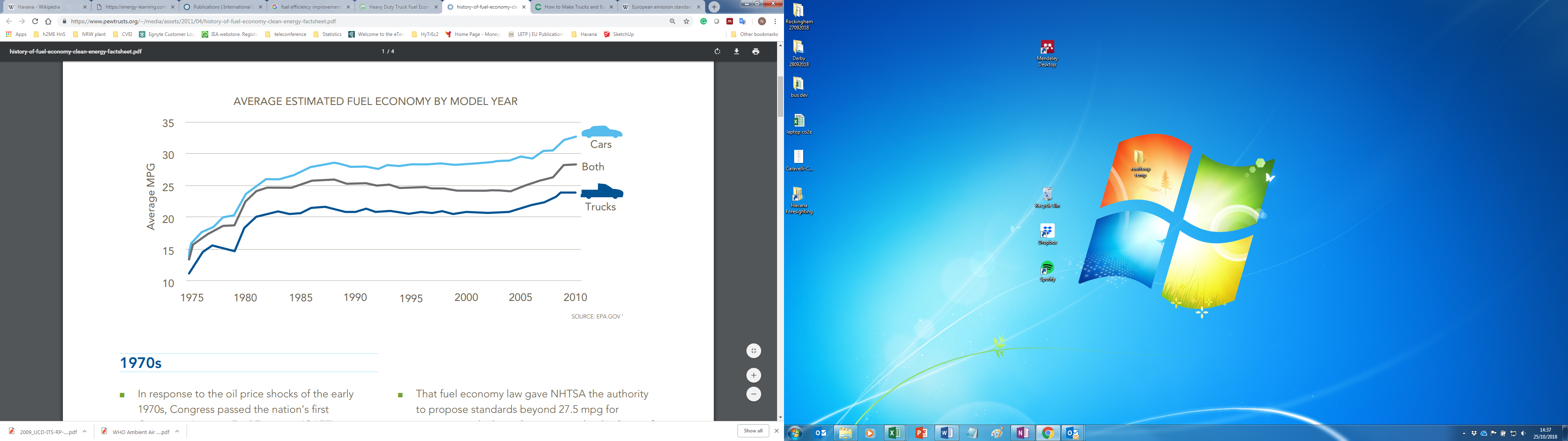
To assess the impact of the uptake of improved internal combustion technologies, Cenex modelled two scenarios for bus replacement in the Havana fleet:

* An EU III uptake scenario, which assumes equivalent emission profiles to UK Euro III standard vehicles
* An EU VI uptake scenario, which assumes equivalent emission profiles to UK Euro VI standard vehicles

Buses can be categorised as heavy goods vehicles (HGVs) for transporting people, so the estimated improvements in fuel economy used in the Cenex model are based on known HGV emissions data. Therefore, the above modelled scenarios used the COPERT based estimates for HGV emissions and fuel efficiency, during 2000 to 2013. COPERT is the EU standard vehicle emissions calculator. It uses vehicle population, mileage, speed and other data such as ambient temperature and calculates emissions and energy consumption for a specific country or region.

US data on fuel efficiency for HGVs provides a guide to the relationship between EU standards and emissions. Their level of fuel efficiency was largely static through this period, the estimated fuel efficiency of the Havana bus fleet was set the same for both the EU I and EU III scenario. The US has had a relatively slow uptake of low emission buses, but with the latest generation of vehicles, a 25% improvement in fuel efficiency has been recorded, as shown in Figure 4. This 25% improvement is reflected in the revised fuel efficiency value for the EU VI scenario, shown in Table 5.

*Figure 4: Historic US fuel economy improvements*



*Source: US EPA*

#### EU III and EU VI equivalent scenarios

*Table 5: Havana bus fleet scenarios assumptions*

|  |  |  |  |
| --- | --- | --- | --- |
| Scenario | Distance travelled per year (km) | Duty cycle | Fuel efficiency (litres/ 100km) |
| EU I Baseline | 55,980 | Mostly congested | 101 |
| EU III | 55,980 | Mostly congested | 101 |
| EU VI | 55,980 | Mostly congested | 81 |

Based on the fleet and operational data provided by the Open University (see above table) Cenex have modelled the current (EU I Baseline) Havana bus fleet emissions, and the emissions in the two alternative scenarios, EU III and EU VI, with the results shown in table 6:

*Table 6: Cenex modelled Havana bus fleet annual emissions estimate for three scenarios*

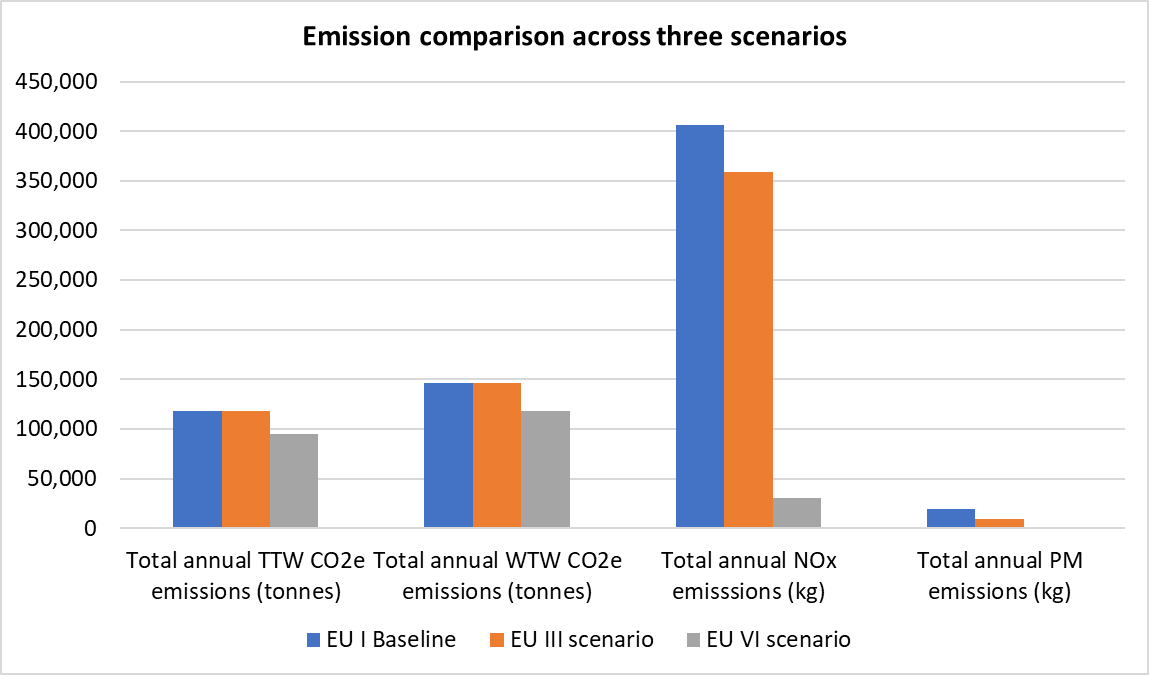
|  |  |  |  |
| --- | --- | --- | --- |
|  | EU I Baseline  (tonnes per annum) | EU III scenario  (tonnes per annum) | EU VI scenario (tonnes per annum) |
| Annual Well to Wheel CO2e emissions | 146,109 | 146,109 | 117,931 |
| Annual Tank to Wheel CO2e emissions | 118,266 | 118,266 | 95,457 |
| Annual NOX emissions | 406 | 359 | 30 |
| Annual PM emissions | 19 | 9.7 | 0.3 |

As can be seen in Figure 5, the modelled CO2e emissions do not change between the baseline (EU I) scenario and the EU III scenario as they assume the same fuel consumption. However, in the EU VI scenario, the improved fuel efficiency leads to an improvement in CO2e emission for both Tank-to-Wheel and Well-to-Wheel emissions is shown of 19%.

The reduction in NOX and PM from the baseline EU I standard, in both the EU III and IV scenarios, is typical of the improvements witnessed in other studies. The improvements in air quality that could be achieved are substantial and would, in turn, have significant health benefits for users of the Havana public transport network, bus drivers, and those who live close to bus routes.

It should be noted that the Well-to-Wheel estimates are based on UK data, and are likely to vary for Cuban fuel supplies. Therefore, a full life-cycle analysis based on the projected Cuban fuel supply chain may be a topic for future research.

*Figure 5: Emission comparison for Havana bus fleet scenarios*



#### Methane gas scenario

In a dedicated gas engine, methane is combusted in a spark ignition engine, with a typical efficiency reduction of 20-25% compared with a diesel engine. These engines produce significantly lower noise, and normally lower particulate matter and NOX emissions, than their diesel counterparts. Gas powered vehicles can store their fuel on the vehicle in compressed or liquified form and, when operated on 100% biomethane (methane produced by the anaerobic digestion of organic matter), they can offer around 60-85% well-to-wheel CO2e emission savings compared to their diesel equivalents.

A simplified analysis of the Havana bus fleet data provided by the Open University uses UK yield data shown in Table 7. This which assumes that methane is produced via the anaerobic digestion for a range of base materials.

*Table 7: UK estimated yields of biomethane production*

|  |  |  |
| --- | --- | --- |
| Base Material | Yield Factor (m3/tonne) | |
| **Single Stage Digestion** | **Multi Stage Digestion** |
| Raw sewage sludge | 55 | 60 |
| Dairy cattle | 16 | 18 |
| Pig manure | 16 | 18 |
| All poultry | 95 | 105 |
| Food waste | 80 | 90 |
| Animal by-products | 110 | 120 |
| Municipal Solid Waste (MSW) | 70 | 75 |
| Green waste | 60 | 65 |
| Energy Crops | 80 | 90 |

However, due to the differences in engine efficiency between diesel and methane powered engines, the analysis highlights that methane-fuelled engines require more fuel throughput, as shown in Figure 6, below.

*Figure 6: Estimated fuel consumption for Havana bus fleet*

Despite higher fuel consumption, a dedicated methane powered fleet has the potential to reduce overall emissions. Figure 7 highlights the potential CO2 savings that could be realised through the use of methane within the Havana bus fleet. In addition, a 20% reduction in emissions such as NOX and PM are also possible if direct injection methane engines can displace diesel engines, resulting in a significant improvement in air quality.

An annual fuel cost-saving may also be possible if methane supplies (either as natural gas, biomethane or some mixture of the two) can be sourced more cost-effectively than diesel.

*Figure 7: WTW CO2e emissions estimate comparing EU VI engines running on petrol/diesel to biomethane*

However, it must be stressed that the case for methane fuelled transport is not yet clear-cut or proven. Direct injection methane engines are still being trialed in the UK. While initial results are promising, more data is required to understand the long-term emission and operating cost impacts.

Methane produced through biological processes such as anaerobic digestion has the potential to capture more CO2 than it emits as part of the methane production process. However, methane is a very potent greenhouse gas (GHG) and any lapse in the containment of the methane over the life of the vehicle (for example leaking fuel lines or fuel stores) rapidly eliminates any economic or environmental benefit.

If methane and biomethane based bus fleets are of interest, a more detailed study on the viability of direct injection methane engines and sustainable methane production is required.

## 

## Alternative powertrains: hybrid and electric technology

However, to enable the Havana Transport Authority to generate emission savings beyond that achieved through EU VI powertrains, it will be necessary for them to make the transition to ultra-low emission vehicle (ULEV) technologies[[4]](#footnote-4), such as hybrid electric, battery electric or hydrogen fuel cell power. The main ULEV technologies available to achieve this are briefly summarised in Table 8.

***Table 8: Overview of alternative powertrains***

|  |  |
| --- | --- |
| Alternative Powertrain | Description |
| Battery electric vehicle (BEV) | A vehicle that is powered purely by electricity which is stored in a traction battery |
| Hybrid electric vehicle (HEV) | Also known as a parallel hybrid; a vehicle that uses a combination of an Internal Combustion Engine (ICE) and one or more electric motors to power the vehicle. The vehicle can be driven on either of these motive sources |
| Plug-in hybrid EV (PHEV) | A hybrid electric vehicle with a relatively large traction battery able to be charged from external electricity supply, typically offering a modest electric-only driving range |
| Range Extended EV (REEV) | Also known as a series hybrid; a pure electric vehicle with the ability to charge the traction battery from an onboard generator, typically powered by petrol, diesel or fuel cell technology |
| Flywheel hybrid | A vehicle that uses the rotation of a flywheel to store energy normally lost during braking and deceleration events. This energy is then fed back into the driveline during subsequent driving to reduce fuel consumption |
| Hydraulic hybrid | A vehicle that uses pressurised fluid to store energy normally lost during braking and deceleration events. This energy is then fed back into the driveline during subsequent driving to reduce the fuel consumption |
| Fuel Cell EV (FCEV) | A vehicle that combines hydrogen and air through a fuel cell to create electricity, which is then used to propel the vehicle |

### 

### Alternative powertrain technologies

#### Hybrid electric powertrains

Diesel electric hybrids are the most common form of low emission bus technology in the UK to date.

A hybrid bus combines two power sources within the vehicle powertrain: a conventional diesel engine and an electric motor. The hybrid system enables energy to be recovered during braking and then released to accelerate the vehicle. There are several different types of hybrid architectures such as series, parallel, flywheel and micro-hybrid. These powertrain systems can be used with various types of energy storage, (using chemical batteries or mechanical flywheels for example).

The typical configuration is to combine a conventional internal combustion engine propulsion system with an electric propulsion system. These types of buses normally use a diesel-electric powertrain and are also known as hybrid diesel-electric buses.

Hybrid buses currently cost approximately 50% more than conventional diesel buses. Transport for London purchased hybrid diesel-electric double-decker buses for approximately €320,000 each in 2012.

#### Battery electric powertrains

A battery electric bus is driven by an electric motor that obtains energy from on-board batteries. Battery electric buses offer zero-emission, quiet operation and higher rates of acceleration compared to traditional buses. Unlike trams or trolley buses, they require no constant grid connection and allow routes to be modified without infrastructure changes. They typically use regenerative braking to recover braking energy and thus increase efficiency. However, battery electric buses require very large, expensive and heavy battery units, which can reduce the seating capacity of the vehicle.

China currently dominates the electric bus market: 97% of electric buses and 75% of the batteries in these vehicles are currently produced in China. Table 9 lists some of the leading electric bus manufacturers worldwide.

*Table 9: Worldwide EV bus manufacturers*

| **Company** | **Vehicle Type** | **Technology Type** |
| --- | --- | --- |
| **BAE Systems (UK)** | Hybrid bus, EV bus | hybrid electric and all-electric drive fuel cell systems |
| **New Flyer Industries Inc (Canada)** | heavy-duty transit buses | Prototype all-electric 40-foot heavy-duty transit bus. |
| **WEG (Brazil)** | H2+2 Bus | Hydrogen-electric hybrid |
| **WEG (Brazil)** | Itaipu Bus | Ethanol-electric hybrid |
| **Solaris (Poland)** | Single deck buses | Hybrid diesel electric |
| **Wright Bus (UK)** | Single deck, double deck buses | Hybrid diesel electric |
| **Volvo (Sweden)** | Single deck bus (7900, 7700) | Hybrid diesel electric |
| **Alexander Dennis (UK)** | Single & Double deck | Hybrid diesel electric |
| **Build Your Dreams (China)** | Single deck coach | Battery electric |
| **Zhuhai Guangtong Automobile Company Ltd (China)** | Single deck coaches and city buses | hybrid electric and battery electric |
| **Zonda Bus (China)** | Single deck coaches and city buses | Battery electric |
| **BredaMenarinibus (Italy)** | Single deck transit bus | Battery electric |
| **Tecnobus (Italy)** | Single deck transit bus | hybrid electric and battery electric |
| **Optare (UK)** | Single deck transit bus | Battery electric |

The pace of the mass-market roll-out of electric and hybrid buses will be dependent on advances in battery technology – principally improvements in cost, performance and safety. Battery cost reductions are expected to arise from economies of scale and productivity gains arising from increasing sales volumes, which will be driven by the larger market of passenger cars rather than buses.

Currently, nickel metal hydride (NiMH) is the dominant battery chemistry for hybrid applications for passenger cars, but lithium ion (LiIon) chemistries offer the most promising combination of power and energy density and are used in battery electric buses.

There is some uncertainty about the lifetime of different models of electric bus batteries, but the available information indicates that they typically need replacing after 6 to 8 years, by which time approximately 20% of the original battery capacity has been lost. In the UK, the typical lifespan of buses ranges from 17-20 years across a mix of primary and secondary operations. It is therefore likely that the batteries will have to be replaced at least once during the operational life of a bus. Battery replacement represents around 50% of the purchase price of an electric bus and 15% of the purchase price of a hybrid bus.

Research undertaken by Transport & Environment, assessed the impact on the total cost of ownership (TCO) calculation when external costs on health and climate were included. These externalities are not reflected in standard TCO calculations and are used to indicate how much noise, air pollution and greenhouse gas (GHG) emissions cost to society.

When external costs are excluded, electric buses are marginally more expensive to operate that equivalent diesel buses; 0.94 €/km for a diesel bus versus 1 €/km for an electric bus. When external costs are included, the TCO shows that electric buses are marginally cheaper to operate that the equivalent diesel buses; 1.04 €/km for a diesel bus versus 1.01 €/km for an electric bus. It should be recognised that this analysis was undertaken using an EU IV baseline for the diesel buses. In the case of Havana, with an EU I baseline, the external health and environmental costs will be much higher, thus improving the TCO for electric buses.

The purchase costs of battery electric buses remain higher, with a purchase price typically twice the cost of a regular diesel bus. However, these higher capital costs are mitigated by much lower operational costs due to the use of electricity as a fuel source, which is cheaper than diesel. As battery prices drop due to economies of scale and investment in R&D, the purchase price of electric buses are expected to drop.

### Infrastructure for electric buses

The high-power demand of electric buses coupled with the duty cycle demands of operations present particular demands on operating and recharging battery electric buses. This section of the report focuses on the infrastructure options for battery electric bus recharging, including:

* Normal (slow) overnight charging back at base.
* Quick and/or opportunity charging during the buses’ operating period.

Other electric recharging technologies are also briefly considered, including battery swap and wireless charging; the latter is receiving considerable attention from a number of bus operators and recharging equipment manufacturers at present.

#### Battery recharging infrastructure types

Workplace charging points are typically rated at 3.7 kW (16 Amps) or 7kW (32 Amps) power output and can reduce battery electric car charging times by about 2 and 4 hours, respectively (when compared to a standard 3 kW household three pin connection).

Direct Current (DC) Quick Charging Points offer a convenient and rapid means of charging a electric car battery from flat to 80% in up to 30 minutes, and for bus batteries in around one hour. The units are generally larger than a typical single-phase fast charging point and are akin to a forecourt petrol pump in appearance.

DC Quick Charging Points generally provide between 50-70kW of power output at up to 550 Volts and 125 Amps. This means that a suitable three phase electricity supply must be present in order to connect the charging point to the grid network and therefore installation usually involves liaison with the equipment supplier, land owner(s) and the Distribution Network Operator (DNO).

*Table 10: Battery recharging infrastructure types and costs in the UK*

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Charger** | **Type and**  **recharging time** | **Power** | **Average charger cost (£, ex. VAT)** | **Average installation cost (£, ex. VAT)** |
| **Double Type 2 socket (ground mounted)** | Normal/slow  8-12 hours | 3kW | 3,300 | 4,400 |
| **Double Type 2 socket ground mounted** | Fast  2-4 hours | 7kW | 3,100 | 4,100 |
| **DC Single outlet** | Quick/rapid  < 1 hour | 50kW | 10,000 | 35,000 (including new 3 phase supply) |

#### Wireless charging

With their generally predictable routes, passenger buses present an attractive market for wireless opportunity charging. Overnight slow charging, coupled with en-route opportunity charging allows flexibility of operation, with the particular advantage of allowing bus batteries to be sized appropriately according to the amount of opportunity charging afforded by the bus route and installed wireless infrastructure. Example include:

* Conductix-Wampfler has been demonstrating its system on around 30 electric buses in Genoa and Turin since 2002 with Italian public transport companies AMT and GTT.
* Mitsui-Arup are leading a consortium including Arriva, Conductix-Wampfler and Wrightbus to demonstrate a wireless electric bus charging system in Milton Keynes in Summer 2013.

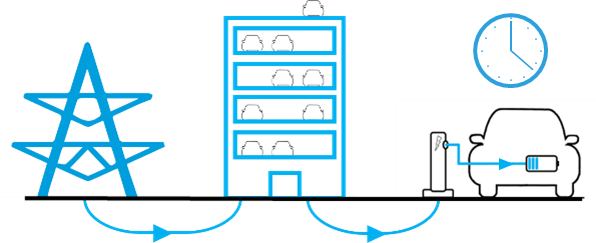
Although there is growing interest in wireless bus charging, a number of issues remain such as:

* feasibility: wireless charging systems require precise location of the vehicle’s inductive receptor over the induction loop on the roadway, which can cause delays and thus limit the amount of ‘opportunity charging’ that is actually achievable at bus stops or junctions. Thus the main opportunity for wireless chargin is at the end of the route, so that the system may be best suited to small routes with difficult terrain. (A trial in Genoa is investigating this.)
* efficiency: all systems on the market claim efficiencies in excess of 90%, comparable to wired transfer, although this does not appear to have been independently verified.
* Safety: compliance with appropriate electromagnetic interference standards such as PC69.
* Infrastructure impacts and requirements.
* Costs: little/no cost data is available on these system and associated infrastructure.

#### Smart charging and vehicle to grid

EV charging represents an entirely new source of electricity demand which neither the buildings nor local low voltage distribution networks were designed to manage. Small numbers of EVs can easily be accommodated but large numbers charging at peak hours can have a significant impact on the peak demand for the site and for the local network. As a result, DNOs need to ensure that networks can cope with the extra demand. This can be done through costly upgrades to meet the new peak demand or through better utilisation of existing capacity. ‘Smart’ charging and Vehicle-to-Grid (V2G) are two key tools for addressing this problem.

*Figure 8: Smart Charging Definition*



**‘Smart’ Charging:** The ability for electric vehicle supply equipment (EVSE) to control the timing of charging and the power output level in response to a user-defined input or signal. However, energy flow is single directional (EVSE to vehicle).

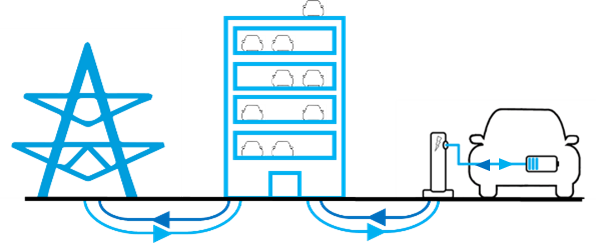
EV smart chargers, which enable ‘managed’ charging, are a commercially available product which enables the user to have greater control over their charging and provide a method for accessing third party services. Smart chargers can vary in their functionality, however as a minimum, smart chargers tend to include scheduling of charging and local load balancing – enabling multiple charge points on a site to be managed to limit their combined electricity demand. Smart charging also enables dynamic demand shifting which can then be used to provide energy services including:

* Time of use (TOU) tariff optimisation.
* Peak demand shaving.
* Network constraint management.
* Simple renewable optimisation.

*Figure 9: Vehicle-to-Grid Definition*

**Vehicle-to-Grid (V2G):**

A system whereby plug-in electric vehicles, when connected to electric vehicle supply equipment (EVSE), can provide bi-directional flows of energy.



As well as smart charging, research projects are currently investigating the opportunity for providing Vehicle-to-Grid (V2G) chargers. V2G allows energy to be discharged from the EV back into the building or local network. This can be used to ‘store’ cheap energy within the EV for use to meet the general building demand later on, or to export electricity back to the network at times when demand on the network is higher than supply.

#### Battery swap

Battery exchange systems have been proposed as a solution to electric bus range limitations; swapping a depleted battery for a fully charged one. For passenger cars and taxis, and in countries with relatively low vehicle numbers and low numbers of vehicle variation are an example where battery exchange may work well. This model was trialled for taxis at Amsterdam Airport, as part of Project Better Place, which was supported by Renault/Nissan. However, Better Place filed for bankruptcy in May 2013 due to financial difficulties caused by the high investment required to develop the charging and swapping infrastructure and a market penetration far lower than originally predicted.

In buses, there has been indications of deployment of battery swapping for buses in China, for example at the 2008 Beijing Olympics. That said there are a number of significant issues which make battery swapping a difficult proposition for bus operations:

* The weight of batteries rated at anything up to 100kWh.
* One of the advances in electric bus battery integration cited by manufacturers has been the ability to distribute battery modules within the vehicle chassis to allow the single vehicle platform to host multiple powertrains, and potentially to be re-engined at the end of its initial operating period.
* From a safety perspective, the electrical connection between the battery and the vehicle carries a very high current, and it is this connection that would need to be made and broken each time the battery is exchanged.
* There are considerable implications in terms of finding space in bus garaging facilities to facilitate battery exchange.

DC fast charging would appear to offer a better solution, providing a charging regime can be established to permit the local grid to support simultaneous bus charging when necessary.

### Electric buses: maintenance

#### Measuring the impact of maintenance regimes

There are key maintenance procedures that have a direct and quantifiable impact on fuel consumption such as tyre inflation pressure, or the amount of fouling on air intakes and fuel injectors. The economic impact of fuel and air intake-filter fouling can be estimated by original equipment manufacturers with reasonable accuracy. The impact of tyre pressure on fuel efficiency and tyre lifetimes are also well understood. Taken together (engine fouling and insufficient tyre pressure) up to a 12% increase in fuel consumption are representative.

When it comes to the frequency of other maintenance procedures, there is little direct evidence to define the preferred ratio between scheduled and unscheduled maintenance. There is an industry standard ‘rule-of-thumb’ that 80% of maintenance staff time should be scheduled (preventative) and 20% should be unscheduled.

To assess the impact of maintenance regimes, many transport authorities will choose a measurable, easily quantifiable assessment of bus performance. There is no “industry standard” method of measurements. However, several of the most common methods are detailed below; these measurements methods can be both a ‘per-vehicle’ basis and used as a fleet wide measure:

* Operational day and days lost ratio (a simple measure easy to monitor and report, additional record keeping is required to define the reasons for lost operational days, can fail to record failures that happen outside of scheduled service times)
* Public transport service interruptions (can fail to record failures that happen outside of scheduled service operation routes)
* Hours of operation without mechanical failure incident (Effectiveness is constrained by the in-house definition of ‘mechanical failure’, can fail to record failures that happen outside of scheduled service times)
* Number of road side maintenance call outs (also known as ‘road calls’) can miss depot-based failures and vehicle recovery operations if not defined properly

Non-scheduled maintenance can also be further broken down in to categories such as brakes, powertrain, tyres, bodywork, road traffic incident, and so on. Such classifications assist the maintenance teams and management in identifying trends in failures and to mitigate the underlying causes of failure.

The ratio of scheduled to non-scheduled maintenance must be defined by the operating organisation. The ratio is set to limit service interruptions to an acceptable level and achieve overall operational cost savings. This ratio is often termed the preventative maintenance interval (PMI). PMI is usually time based, distance based, or a combination of the two. The PMI may be route specific for some vehicles (for example, vehicles with a steep incline in the route may receive more frequent checks on brake pads, disks and brake fluid). The PMI may very due to local conditions (for example periods of prolonged rain may require brake-disc refurbishment in the following month).

#### Maintaining electric vehicles

Hybrid electric and battery electric vehicles may seem complicated and daunting and can cause confusion when trying to service, repair or diagnose a system fault. In addition to this, safe working practices must be adopted during routine service and repair, as well as when components are removed and refitted. Note that a key difference between electric vehicles (either hybrid or all-electric) and conventional buses is the high voltage/amperage of electricity passing around the vehicle. This is higher than any domestic explosure to electricity, and therefore a significant hazard, making investment in adequate training essential. Therefore, all vehicle repair professionals should attend training before attempting to service or repair any hybrid or electric vehicle, given the safety critical procedures that must be adhered to during maintenance. Workshop staff and technicians require a complete awareness of the risks and hazards associated with HEVs and must follow the recommended safety measures required during maintenance. This is necessary not just for the safety of the technician, but any employees or customers who may come into contact with the vehicle whilst in the workshop.

In the UK, health and safety law specifies a legal requirement for training on high voltage vehicles. This is also interpreted into industry standards such as BS 10125 which provides guidance for body-shops and accident repair centres calling for EV Hazard Management and Awareness training to be undertaken for technicians working on HV vehicles. In addition, vehicle manufacturers require external technicians to have bespoke training on their vehicles, to the same competency level as their dealer network.

Limited information was available on the current costs associated with the training of technicians on maintaining electric buses in the countries in which they operate. The information provided below is therefore based on the costs associated with the training of technicians to service an electric car in the UK, as an example.

#### Training modules and costs: UK

In the UK, training Colleges often offer four levels of training. While the basic safety training provided at level 1 is free, the amounts charged for higher levels reflect UK labour costs and overheads.

*Table 11. UK training colleges: modules and costs, for illustration*

|  |  |  |
| --- | --- | --- |
| Level of Training | Scope | Duration & Cost |
| Level 1: Awareness | For employees working around, but not on, high voltage systems (e.g. workshop office staff). | Free online course |
| Level 2: Hazard Management | For personnel interacting with a high voltage vehicle (e.g. valeters, fleet drivers, breakdown personnel etc.) | 0.5 day / £150 pp |
| Level 3: Electrically Propelled Vehicle and Replacements Training | To give qualified motor technicians add-on knowledge for HV vehicles with modules in Safety Around HV systems, Awareness, Hazard Management, Service Repair and Replacement. Does not cover live working (e.g. battery cell replacement). | 2 day / £500 pp |
| Level 4: Live Working | To train technicians to work on live batteries and HV systems | Price on demand |

Vehicle manufacturers also provide training for professional certified maintenance engineers, tailored to the specific requirements for their electric vehicles, intended for high voltage automotive safety and vehicle specific maintenance procedures. Top-up training would then be available to cover minor changes and new model releases. As an example, the table below outlines e-NV200/Nissan Leaf service training packages:

*Table 12. Nissan Leaf service training modules and costs, for illustration*

|  |  |  |
| --- | --- | --- |
| Level of Training | Scope | Duration & Cost |
| Basic Awareness | Aimed at technicians working on non-EV related aspects (tyres, wheels, brakes, windscreen wipers etc.). | 2-3 days / £500 – £750 pp |
| Service and Maintenance | Aimed at technicians undertaking annual service and general maintenance and repair requirements (excluding battery and power distribution modules). | 2 weeks / £2,250 pp |
| Advanced Level Training | Aimed to allow all repair work to be undertaken (battery, power electronics, motor replacements etc.). This is additional to Service and Maintenance level training. | 2 weeks / £2,250 pp |

#### Servicing equipment

Beyond the personnel training required, there are likely to be additional equipment costs as detailed below:

* Access to manufacturer electronic manual service
* Personal Protection Equipment (£70)
* High Voltage Lockout Plug (£200)
* Voltage Absence Tester (£63)
* Insulation Tester (£340)
* Nissan Consult Diagnostic Tool and Licence (£3,500 + £240/annum)

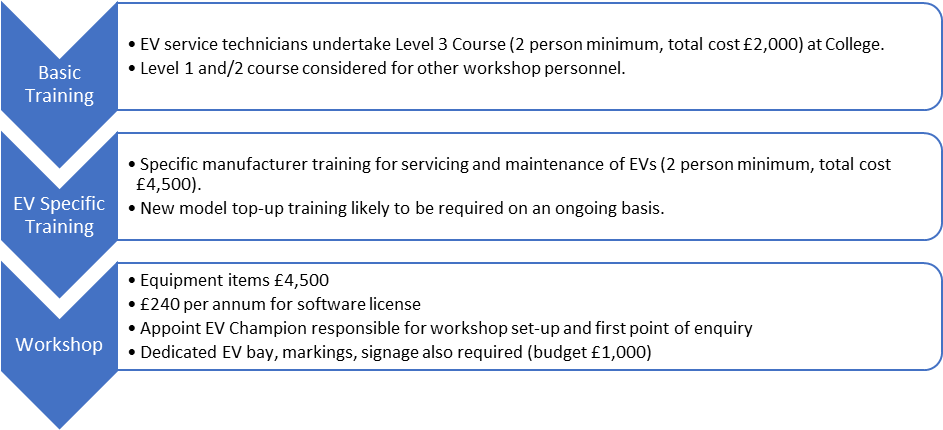
#### Other workshop and servicing requirements

Manufacturers will have additional workshop guidance for EV servicing which typically include a dedicated bay with appropriate markings for EV maintenance, two trained technicians to be onsite during EV maintenance work and hazard signage.

However, most manufacturers prefer to keep servicing and maintenance of their vehicles in-house, at their dealers. Both Nissan and Mitsubishi only reluctantly provide self-servicing training and provide such training packages only if customers demand them. While servicing ‘out-of-network’ does not necessarily invalidate vehicle warranty, it is likely to do so unless genuine parts (or equivalent) are used and official manufacturer service schedules are adhered to.

The flow chart below summaries the three main stages of actions required to enable fleet operators to service EVs. The basic costs estimate, based on UK prices, is £12,000 to train two workshop technicians and purchase equipment required to service and maintain Nissan Leaf and e-NV200. Further vehicle makes (e.g. Mitsubishi, BMW etc.) may cost circa £9,000 each for initial training and equipment. High level training (e.g. live working) is not required for the initial set up, as this is likely to be infrequent and more appropriately undertaken at the main dealer.

*Figure 10: Electric vehicle training progression*



## Hydrogen fuel cell buses

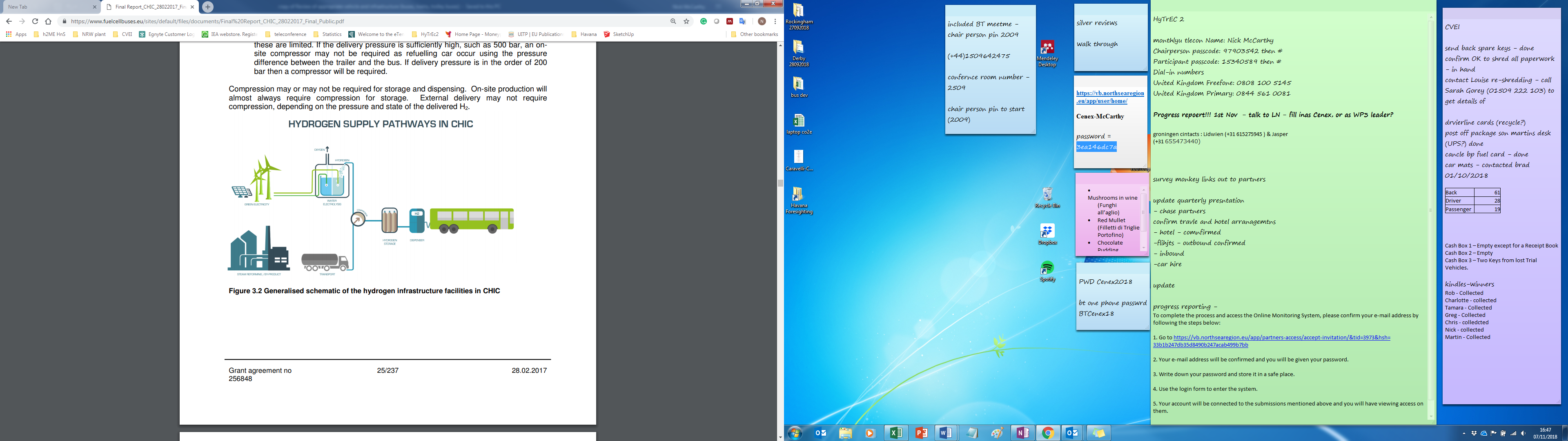
Hydrogen fuel cell buses are broadly similar to electric buses, and are classified as electric vehicles. The key difference is that the vehicle utilises hydrogen gas as an energy carrier instead of electricity provided by the battery system. The hydrogen is passed through a fuel cell, where combines with oxygen in an electrochemical reaction to generate the electricity used to power the vehicle, along with water which is the only exhaust product. For bus fleets with less capacity for vehicles to be offline, the faster speed of refuelling for hydrogen vehicles can be an attractive alternative. However, it should be noted that the use of hydrogen as a fuel remains in its infancy, therefore there is limited availability of vehicles and associated refuelling infrastructure, and the costs are very high.

While fuel cell electric buses produce no harmful local emissions, some forms of hydrogen fuel production generate carbon dioxide. Currently, the majority of hydrogen used in industry is produced by reforming natural gas which when used in buses offers slightly reduced CO2 emissions compared to diesel buses (EU VI models) on a well to wheel basis. The use of hydrogen produced from natural gas can be an important first step in the early years of deployment from a cost perspective. However, of more interest is the use of low‐carbon hydrogen production methods. Of these, the option of electrolysis from renewable energy sources is the most mature. This allows the buses to reach full carbon neutrality from a well to wheel perspective and hence to significantly reduce CO2 emissions. Low carbon hydrogen can also be generated from biomass, waste, direct from nuclear or solar heat, from fossil hydrocarbons using carbon capture and storage or as a result of using hydrogen which would otherwise be wasted in industrial facilities. The technology for each of these routes is maturing rapidly and each are expected to lead to plentiful low cost, low carbon hydrogen during the 2030s.

Currently hydrogen fuel cell buses remain expensive: based on orders for 100 buses or more, new buses typically cost €450,000 each in 2016. At the moment there are fewer than 100 hydrogen fuel cell buses worldwide, but over the next five years the EU plans to purchase over 600 in a regional joint procurement programme, at the agreed purchase price of €450,000 each. The EU joint bus purchase programme aims to have 350 hydrogen fuel cell buses in operation by the end of the 2018/19 financial year.

The latest publicly available information on hydrogen fuel cell buses is from the 2016 report on Clean Hydrogen in European Cities (CHIC). The CHIC project gathered data on 54 hydrogen fuel cell and battery hybrid buses and four hydrogen-powered ICE buses in Canada & Europe. The vehicles tested as part of this project achieved a range of between eight to twelve kg of hydrogen per 100 km. The project showed a reduction of the Global Warming Potential (GWP) impact by 43% compared with the diesel bus using the actual CHIC H2 mix. A possible 85% reduction could have been realized if green H2 only had been used. The hydrogen supplied to the bus vehicles was generated from a combination of renewable and fossil fuel sources and provides a viable pathway for the transition to hydrogen fuel cell bus technologies.

*Figure 11: Hydrogen supply pathways in the CHIC bus project*



*Source: Clean Hydrogen in European Cities Final Report*

## Tram and trolley bus systems

Trams and trolley buses are primarily characterised by the requirement for a fixed power line to power the vehicle. Trams were a common sight in many cities before the popularisation of internal combustion vehicles. The tram system is closer to train transport in that they require steel wheels on steel rails, while a trolley bus uses only overhead power lines.

It should be recognised that the above definition is simplistic in nature, due to the scope of this report. Some trams have a single, central, rail for steering and run on rubber wheels which allows them to operate more quietly and access steeper gradients than normal trams. In addition, China is developing a trackless tram which is an optically guided bus, using a painted line in the road as its guide.

An important operational disadvantage of trams is that they are tied to a fixed route, and unable to deviate in case of accidents, congestion, road maintenance or failure of another trolley on the line ahead, causing serious delays in service. Trolley buses sacrifice the higher energy efficiency of steel on steel wheels and rails for a slightly improved flexibility and reduced infrastructure costs. Some trolley buses have limited battery capacity or auxiliary engines which allow the vehicle to disconnect briefly from the power lines to avoid an obstacle in the road or to switch routes.

Efforts to maintain tram systems can be motivated by a desire to maintain links with the past or provide a unique experience for visitors. It has been argued that they offer reassurance to local economies and favour long-term investment and planning for both government and independent businesses, but there is no evidence to indicate that tram systems attract additional investment or funding to the areas where they operate. Some authors also claim trolley buses offer lower variable costs of energy, lower noise and potentially lower CO2 emissions than electric vehicles. However, this is dependent on the energy generation mix supplying the power lines and the maintenance level of the electrical infrastructure over the life of the system.

The emission profiles for both these types of vehicles are similar to that of electric buses, but the systems are more expensive than electric buses due to the added infrastructure cost for installing power lines and dedicated passenger platforms. However, due to the increased capital costs, passenger volume is the primary determinant of the economic viability of these systems. With high passenger volumes, the cost per passenger km can be relatively low despite the increased infrastructure costs. Therefore, the relative benefits of these systems are greatest for longer journeys as well as high passenger numbers.

The capital cost of trolley bus systems are lower than for tram systems. In the case of Havana, with a relatively high proportion of the population dependent on public transport, trolley buses might be suited to some of the busiest routes. However, apart from the cost per passenger km calculation, an additional consideration is the critical importance of a guaranteed power supply.

As noted above, trolley bus and tram systems are generally seen as more expensive than electric buses and therefore require more public funding to install and run.

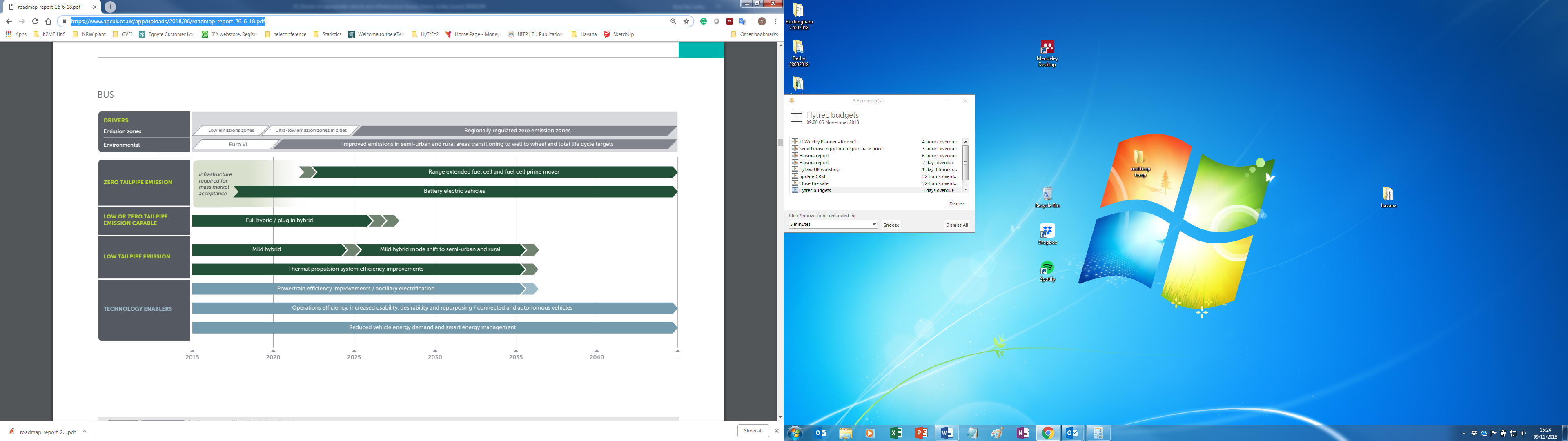
# Technology Suitability Assessment

|  |
| --- |
| **Key Points** |
| **Methodology**  An initial assessment of the suitability of alternative low emission technologies was undertaken, drawing on the information presented above, together with suitable road transport technology roadmaps. A traffic light assessment was then developed and presented for a range of identified technologies.  **Key Results**   * All identified technology options have higher vehicle and infrastructure capital costs and suffer from a lack of available refuelling or recharging infrastructure within Havana. * Those technologies relying on existing, market ready powertrain technologies (i.e. EU III, EU IV and methane) appear to be more operationally suitable than those relying on relatively unproven technologies (i.e. battery electric, hydrogen fuel cell and tram & trolley bus systems).   **Next Steps**   * To make the transition to a low emission bus fleet the Havana Transport Authority will need to assess the wider infrastructure that would be required to use any selected technology option. * Given the continuing market shift towards ultra-low emission vehicle technologies, the Havana Transport Authority will need to develop a transition plan that takes account of changes in technology developments, thus taking advantage of lower cost technologies where appropriate. |

## Technology roadmap

Technology roadmaps are used as a way of collating together information from across the automotive industry (e.g. universities, government departments, automotive manufacturers, etc.) to gain an understanding of the likely pathway for future technological developments. The most recent technology roadmap developed by the UK Automotive Council and the Advanced Propulsion Centre, in Figure 12, provides an overview of the expected evolution of the technologies for bus emission reductions described above.

Figure 12: EU bus powertrain roadmap 2015



*Source: UK Automotive Council and the Advanced Propulsion Centre*

Examining this in more detail, the following predictions can be made:

* **Reduced emission alternative fuels.** Gas vehicles, with blended biomethane, will increase in numbers with infrastructure provision supported through the EU Clean Fuels Directive. In addition, and if proven economic, ‘drop-in’ fuels could be blended in high volumes with standard diesel.
* **Hybrid vehicles.** By 2025 it is anticipated that advances will be made in all types of hybrid systems, and that hybridisation will become the default technology choice for diesel and gas buses.
* **Battery technology.** Advances in battery technology will incrementally improve the range and cost performance of EV buses. Although most initial deployments of EV buses will be subsidised, non-subsidised cost parity may be reached if battery durability is proven.
* **Recharging systems.** Wireless charging deployments are likely to be demonstrated throughout the EU.
* **Hydrogen fuel cell buses**. These will progress to the user-led demonstration phase where funding allows.

As global technological development progresses, the availability of similar technologies for the Cuban market should increase. Before making large investments in replacement vehicles, Havana’s decision-makers have the opportunity to monitor public transport developments elsewhere and adopt solutions that acquire a proven track record.

## Suitability assessment ‘traffic light’ overview

The technology scanning task generates a simplified ‘traffic light’ diagram based on the calculated performance of the following low emission vehicle technologies and their supporting refuelling and recharging infrastructure:

* EU III internal combustion powered
* EU VI internal combustion powered
* Methane powered
* Battery electric powered
* Hydrogen powered
* Trolley bus systems

These technologies are compared to the EU I baseline according to the following criteria:

* **Technology Maturity:** how long the vehicles have been available and used successfully in wide scale public transport applications.
* **Vehicle Availability:** ease of purchase and number of suppliers offering the technology
* **Infrastructure Availability:** high-level assessment of existing infrastructure in Havana and its compatibility with the proposed vehicle technology
* **Capital Cost:** comparison of vehicle purchase price versus baseline technology
* **Running Cost:** comparison of the vehicle running costs (e.g. fuel, maintenance, replacement parts) versus baseline technology.
* **CO2 benefits:** comparison of CO2e emissions compared to baseline technology. This assessment assumes significant effort to include renewables wherever possible.
* **Air quality benefits:** comparison of NOX and particulate emissions compared to baseline technology. This assessment assumes significant effort to reduce air quality through measures such as urea and SCR wherever possible.

In the ‘traffic light’ diagram below:

* **Green** indicates that the technology is superior to the baseline technology, for example, increased operational range or reduced cost of operation
* **Amber** means that the technology is neither worse nor better than the baseline technology
* **Red** signifies that the technology is considered worse than the baseline technology

*Table 13: Technology suitability assessment (in comparison to existing baseline EU I vehicles)*

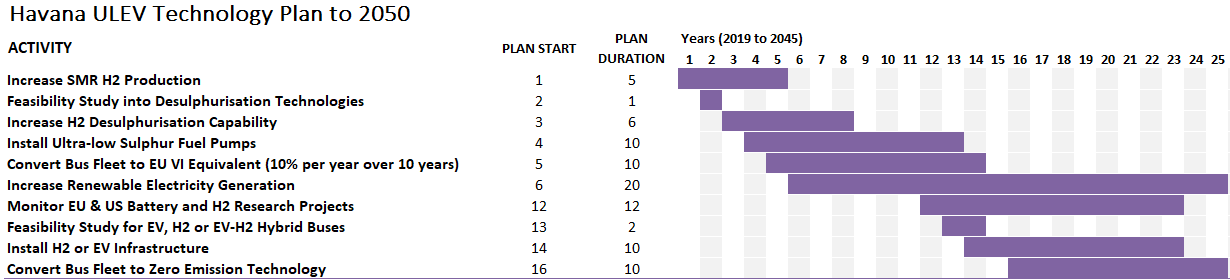
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| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Technology Type | Technology Maturity | Vehicle Availability | Infrastructure Availability  (Havana) | Capital Cost | Running Cost | Operational Range | Refuelling Time | CO2 Benefit | Air Quality Benefit |
| EU III |  |  |  |  |  |  |  |  |  |
| EU VI |  |  |  |  |  |  |  |  |  |
| Methane |  |  |  |  |  |  |  |  |  |
| Battery Electric |  |  |  |  |  |  |  |  |  |
| Hydrogen Fuel Cell |  |  |  |  |  |  |  |  |  |
| Tram & Trolley Bus Systems |  |  |  |  |  |  |  |  |  |

The above table indicates that, for the scenarios explored, there is no simple solution to the decarbonisation of the Havana bus fleet. All identified technology options have higher vehicle and infrastructure capital costs and suffer from a lack of available refuelling or recharging infrastructure within Havana. This means that to make the transition to a low emission bus fleet the Havana Transport Authority will need to assess the wider infrastructure that would be required to use any selected technology option.

It can be noted that those technologies relying on existing, market ready powertrain technologies (i.e. EU III, EU IV and Methane) appear to be more operationally suitable than those relying on relatively unproven technologies (i.e. battery electric, hydrogen fuel cell and tram & trolley bus systems). However, given the continuing market shift towards ultra-low emission vehicle technologies, the Havana Transport Authority will need to develop a transition plan that takes account of these changes in technology developments, thus taking advantage of lower cost technologies where appropriate.

An example transition plan is offered below. It provides a first attempt, taking into account such future developments. Given the limited scope of this report and the limited information upon which it is based, it should be read as a tentative starting point for discussion, rather than a recommendation.

*Figure 13: Havana ULEV transition plan*



As Figure 13 shows, the initial focus the example plan is on a shift towards the use of more efficient diesel vehicles in combination with improved refinery capacity to achieve improved fuel standards (rising from EU III to EU VI), and then a shift towards zero carbon electric or biofuels vehicles.

However, it is noted that sufficient financing may not be available to upgrade the existing refineries, so a more direct transition to zero emissions electric and biofuels might be more appropriate. The possible availability of climate finance (for mitigation of greenhouse gas emissions) might make such a ‘leapfrog’ approach more feasible and appropriate.

It should also be noted that an increase in the use of electricity by the public transport system would imply additional investment in electricity generation. The contribution to emissions reduction and escaping from oil import dependency would be maximised if the necessary new power generating capacity were to be from renewable sources. The government’s current target is to achieve 24% of electricity generation from renewables by 2030, based on current projections for electricity consumption that do not envisage a switch to electric buses. Therefore this analysis suggests that a review of targets for renewable energy generation needs to be considered together with public transport technology choices.

## Total cost of ownership

Typically, fleet assessments such as the one presented in this document would include an assessment of “Total Cost of Ownership” (TCO). In the case of transport applications, Cenex would typically model vehicle TCO using the following inputs:

*Figure 14: Factors determining vehicle total cost of ownership*

There is extremely limited data on the economics of the bus fleet currently operated by the City of Havana Authority. Critical information such as purchase price, real-world cost of diesel, drive cycles distribution across the fleet, fuel consumption rate per vehicle or the man-hours spent on maintenance of the existing fleet, were not available. This lack of information makes a TCO analysis of the existing fleet impossible.

However, Cenex can assist City of Havana Authority in undertaking the necessary data capture to complete a TCO assessment of their bus fleet if required. To complete a TCO analysis for the City of Havana Authority on their bus fleet, the following actions would be required:

1. Ensure compatibility of Cenex data capture devices with Cuban mobile telephone communications.
2. Undertake a fleet and route assessment to define statistically representative vehicles and routes (a “design of experiments” approach).
3. Install Cenex CLEAR Capture vehicle tracking devices. Vehicles to be monitored for a minimum of two months in each season (for example, Winter/January, summer/May and the rainy-season/August). Vehicle monitoring to include accurate record keeping of fuel consumption and all maintenance on monitored vehicles.
4. City of Havana Authority to supply detailed technical specifications for all monitored vehicles.
5. Development of controller area network (CAN-bus) signals processing and data capture for representative vehicles (exact number required to be determined after completion of a fleet and route assessment).
6. Baseline measurements of bus performance to a standard drive cycle on a closed road, race track or vehicle proving ground (Including direct access to CAN BUS signals).
7. Cenex to adapt existing vehicle models of bus performance to a Cuban context.
8. Cenex to report a fleet wide TCO analysis, with recommendations for low and zero emission technology specifications for the Havana bus fleet.

# Summary & Conclusions

The conclusions of this initial study are preliminary and tentative, due to its limited scope and in the absence of specific and relevant operational data on the Havana bus fleet. Much of the analysis uses performance data and cost estimates from UK and EU low emission bus projects, so may not be directly applicable to operations undertaken within Havana. More information is needed to provide more precise estimates.

However, the analysis does indicate the range of benefits that the City of Havana authority could gain by utilising low emission buses. These include reduced emissions of particulate matter (PM), nitrous oxides (NOX) and carbon dioxide (CO2e), in addition to reducing the total cost of ownership.

For the scenarios explored, there is no simple solution to the decarbonisation of the Havana bus fleet. All advanced technology options identified in this report imply additional vehicle and infrastructure capital costs. Before embarking on a transition to a low emission bus fleet, the Havana Transport Authority needs to assess the wider infrastructure that would be required to use any selected technology option.

It can be noted that, at present, those technologies relying on existing, market-ready powertrain technologies (i.e. EU III, EU IV and methane) appear to be more operationally suitable for investment than those relying on relatively unproven technologies (i.e. battery electric, hydrogen fuel cell and tram & trolley bus systems). However, given the continuing market shift towards ultra-low emission vehicle technologies, the Havana Transport Authority will need to develop a technology transition plan that takes account of the ongoing technological advances and resultant changes in relative costs, to take advantage of lower cost technologies when and where appropriate.

This study has identified the potential to displace 28,000 tonnes of well-to-wheel CO2e per year and reduce air quality emissions by 376,000 kg of NOX and 19,000 kg of PM if a transition to an EU VI emission profile is adopted. However, the deployment of lower emission conventional vehicles, such as EU VI diesel powertrains, would require the use of low sulphur fuels. This would necessitate investments to improve the refinery level desulphurisation process to ensure the reduction of sulphur-based compounds to 15 parts per million (PPM) or less, as well as the installation of dedicated low sulphur fuel pumps at all depot-based refuelling sites.

A critical choice for the City of Havana is whether to bypass existing conventional diesel technology and adopt battery electric buses for some or all of its fleet, and if so, when and how to do so. This transition from conventional technologies to much newer ones could provide more substantial well-to-wheel CO2e and air quality emission benefits than simply replacing oil buses with lower emission conventional vehicles. However, further data would be needed to undertake a full and detailed analysis of these options. For the adoption of electric vehicles, the costs of reinforcement of the local electricity grids through the installation of dedicated substations and associated charging stations would also need to be taken into account.

To shift to tram or trolley bus systems, power lines – either overhead or ground-based – would need to be installed and maintained throughout the bus routes they operate on. Such fixed route solutions are not only more expensive than the alternatives but also offer limited flexibility if passenger demand changes, or if there is damage, power cuts or disruptive maintenance to the road or charging infrastructure on the planned routes.

In current conditions, the ongoing investment in replacing existing buses with hybrids is a positive development in terms of emissions, and an appropriate technology choice. However, as technological advances enable more substantial emissions savings to become available, further, more detailed, research will be needed to ensure that future investment decisions are tailored to the specific operational conditions and vehicle running costs experienced within the Havana Transport Authority, and that plans are made for the necessary infrastructure investment.

Cenex could assist with such research, to provide a more accurate analysis and thus identify those technologies best suited for deployment across Havana.

1. **Bibliography**

Archer, S., ‘Sustainable Hydrogen from Biomass Pathway Investigation Life Cycle Analysis’, University of Birmingham, 2017.

Chandra Srivastava, V., ‘An evaluation of desulfurization technologies for sulfur removal from liquid fuels’, RSC Adv. 2(3):759–783, 2012, doi:10.1039/C1RA00309G.

Check your tyre pressures at least once a month | Care Guide | | Learn and Share | MICHELIN, https://www.michelin.co.uk/tyres/learn-share/care-guide/tyre-pressures, Feb. 2019.

E.B., ‘Why trams are a waste of money - The Economist explains’, https://www.economist.com/the-economist-explains/2014/08/05/why-trams-are-a-waste-of-money, 2014.

Electric buses arrive on time: Marketplace, economic, technology, environmental and policy perspectives for fully electric buses in the EU; Transport & Environment, 2018

Façanha, C., ‘Euro VI for Brazil: A clear path for cleaner skies | International Council on Clean Transportation’, https://www.theicct.org/blogs/staff/euro-VI-for-brazil-a-clear-path-to-cleaner-skies, 2017.

Faltenbacher, M., ‘Performance assessment in JIVE-Capitalising on CHIC and other H2 bus projects Dr. Michael Faltenbacher, thinkstep AG Parallel session 2-eBus performance’, 2017.

Frohman Lubetsky, J., ‘HISTORY OF FUEL ECONOMY One Decade of Innovation, Two Decades of Inaction 1970s n’, 2011.

Fuel Cell Electric Buses: An Attractive Value Proposition for Zero‐Emission Buses in the United Kingdom; Ballard Power Systems Inc., 2016

González, K.F., ‘Cuba’s 2017 energy strategy › Cuba › Granma - Official voice of the PCC’,http://en.granma.cu/cuba/2017-02-22/cubas-2017-energy-strategy, 2017.

Harrop, P., ‘Electric Buses 2018-2038: IDTechEx’, 196, https://www.idtechex.com/research/reports/electric-buses-2018-2038-000543.asp, 2018.

Holdsworth, R., ‘New Bus For London Cost Revealed | Londonist’, https://londonist.com/2013/05/new-bus-for-london-cost-revealed, 2013.

Imagenes, J., ‘Development of emission standards for heavy duty diesel engines in the eu euro i vi fig’, www.imagenesmy.com, Jan. 2019.

Liu, L., Lu, H., Qian, J., and Xing, J., Progress in the technology for desulfurization of crude oil, China Pet. Process. Petrochemical Technol., 2010, oi:10.1097/BOR.0b013e3280113d1a.

Majewski, A.W., ‘Technology Guide: Reference Papers on Diesel Engine and Emission Technologies’, https://www.dieselnet.com/tg, 2018.

Millar Apta, W.W., Slater Fhwa, R.E., Aashto, F.B.F., Skinner, R.E., Fisher, J.W., Fitzgerald, D.J., Martinez, R.E., Mccaig, J.J., Moore, M.W., Philip, C.E., Samuels, J.M., Sussman, J.M., Van, J.W., Hoel, L.A., Linton, G.J., and Sels, L., ‘Monitoring Bus Performance: A Synthesis of Transit Practice’, ISBN 0309060141, 1997.

Müller, K.K., Schnitzeler, F., Lozanovski, A., Skiker, S., and Ojakovoh, M., ‘Clean Hydrogen in European Cities’, 2016.

ONEI, ‘Anuario Estadistico de Cuba 2017.

Roy, R.K., ‘A primer on the Taguchi method’, Van Nostrand Reinhold, New York, ISBN 0442237294, 1990.

SMITHSONIAN.COM, ‘Why the UAE Is Betting Big on Renewable Energy | Sponsored | Smithsonian’, https://www.smithsonianmag.com/sponsored/uae-betting-big-renewable-energy-180967320/, 2018.

Stenström, C., Norrbin, P., Parida, A., and Kumar, U., ‘Preventive and corrective maintenance – cost comparison and cost–benefit analysis’, Struct. Infrastruct. Eng. 12(5):603–617, 2016, doi:10.1080/15732479.2015.1032983.

The Roadmap Report Towards 2040: A Guide to Automotive Propulsion Technologies, Nov. 2018.

Wärtsilä Services Business White Paper Engine Fuel and Operational Efficiency Improving Engine Fuel And Operational Efficiency, Feb. 2019.

Weiß, A., ‘TROLLEY Transport Mode Efficiency Analysis Promoting Electric Public Transport TROLLEY Project Transport Mode Efficiency Analysis: Comparison of financial and economic efficiency between bus and trolleybus systems’, 2013.

Wotec, M. and Wyszomirski, O., ‘The Trolleybus as an Urban Means of Transport in the Light of the Trolley Project Edited by Marcin Wołek and Olgierd Wyszomirski’, 2013.



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Independent, not-for-profit, low carbon vehicle technology experts

1. In a motor vehicle, the powertrain (or drivetrain) comprises the main components that generate power and deliver it to the road surface. This includes the engine, transmission, drive shafts, differentials, and the final drive. [↑](#footnote-ref-1)
2. Energy import dependency, and the resulting vulnerability, are not new. Before 1959 oil imports came from the US, which ended oil supplies and blocked financing after the 1959 revolution. At that time, Cuba was able to turn to the Soviet Union; after the demise of the Soviet bloc, with US sanctions remaining in place, oil imports fell by 40% in three years, resulting in the fuel shortages of the ‘special period’ in which the economy contracted by one third. The only reason why the Cuban economy did not suffer from the high international oil prices of the 2011-15 period was that – along with other countries of the Caribbean, under the ‘Petrocaribe’ initiative – it was protected from the economic impact of high oil prices the availability of financing on favourable terms for Venezuelan oil supplies. [↑](#footnote-ref-2)
3. For example the United Arab Emirates which, despite reserves of 98 billion barrels, has one of the largest solar farms in the world. [↑](#footnote-ref-3)
4. Ultra-low emission vehicles are defined as those that emit less than 75g of CO2e per kilometre travelled. This definition is currently only applicable to cars and vans; however, the UK Government are undergoing industry consultation to develop a definition for buses and trucks. [↑](#footnote-ref-4)