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Environmental assessment of current and future urban buses with different energy sources

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Summary

We perform a comparative life cycle assessment of urban buses powered by diesel, diesel-hybrid, natural gas, fuel cells, and batteries. The novelty of this work lies in the use of a consistent framework across multiple powertrain types considering both current and ‘next generation’ technology levels. This, combined with the variety of energy chains included makes this, to the best of our knowledge, the most comprehensive life cycle assessment of urban buses available to date.

Keywords: LCA (Life Cycle Assessment), public transport, bus, modelling, prediction

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1 Introduction

Although public transport by urban bus is generally more environmentally efficient than with individual passenger cars, conventional buses are still associated with significant local air pollution and emissions of greenhouse gases. Many transport authorities have stated commitments to reduce these impacts or even transition to a zero emissions fleet within the next 15 years [1]. Transport authorities looking to renew their fleets are faced with a decision between multiple bus technologies, each with different strengths and weaknesses as well as infrastructure requirements. This decision is made more difficult by the rapid rate of improvement of advanced technologies such as battery and fuel cell electric buses. Furthermore, because the performance of urban buses depends strongly on operating conditions, the results from different studies and manufacturer information are not always directly comparable.

In order to support these decision makers, we develop a framework that allows consistent comparison of different bus powertrains and energy chain configurations using life cycle assessment. We consider six different powertrain variants: diesel (ICEV-D), diesel hybrid (HEV-D), compressed natural gas (ICEV-CNG), fuel cell electric (FCEV), short range opportunity charging battery electric (BEV-SR), and long range plug-in battery electric (BEV-LR). Though this paper focusses on 2017 and 2030 bus construction years, the model includes all construction years from 1990 to 2030.

The novelty of this work lies in the use of a consistent framework across multiple powertrain types with the same operating conditions to assess energy consumption and operating emissions. A further novelty of the work is that we include the expected performance of the next generation of buses, as it is this technology level that is expected to replace conventional buses. This combined with the variety of energy chains considered makes this, to the best of our knowledge, the most comprehensive life cycle assessment of urban buses available to date.

2 Life Cycle Assessment

We perform cradle-to-grave life cycle assessment using the ecoinvent 3.2 database with the cut-off system model [2] and the Brightway2 software [3]. We include the entire bus material cycle, from production to regular maintenance and end-of-life, as well as the entire fuel cycle and operating emissions. The functional unit of our study is one vehicle kilometer (vkm).

Due to time and space constraints, we limit presentation of life cycle impact assessment results to the two categories that we feel are most relevant for urban public transportation:

- Global Warming Potential (GWP) represents the contribution to climate change due to the emission of greenhouse gases such as CO_2 and CH_4. For this indicator we have selected the most recent global warming potential characterization factors from the IPCC [4], as implemented by the ecoinvent center. GWP is quantified in kg CO_2 equivalents using a 100 year reference time period.

- Particulate Matter Formation Potential (PMFP) considers the human health impacts of fine particles in the air. We consider not only the direct emission of particulates, but also the formation of secondary particulates due to emissions such SO_x, NO_x and ammonia (NH_3). PMFP is quantified in kg PM 10 equivalents. This indicator is calculated using the ReCiPe 2008 method with the hierarchist perspective [5]. We use PMFP to represent the urban air quality aspects of bus operation, as NO_x and particulate emissions are among the most important emissions from buses.

3 Bus modelling

In this presentation we focus on standard 12 m buses. All buses are assumed to have a lifetime of 12 years and travel a total of 750 000 km during their lifetime. We model 6 different bus powertrain types, which are briefly described below:

ICEV-D: Internal Combustion Engine Vehicle – Diesel. This is a standard diesel powered bus that meets European emission level EURO VI. It has a 230 kW engine.

ICEV-CNG: Internal Combustion Engine Vehicle – Compressed Natural Gas. This is a standard compressed natural gas powered bus that meets European emission level EURO VI. It has a 230 kW engine.

HEV-D: Hybrid Electric Vehicle – Diesel. This is a hybrid bus configuration with a 185 kW diesel engine that operates a generator. The wheels are powered by two 75 kW electric motors that are capable of recuperative braking and 150 kW of lithium ion power batteries (15 kWh storage capacity). The bus meets European emission level EURO VI. The bus does not have the ability to recharge batteries from the electricity grid.

FCEV: Fuel Cell Electric Vehicle. This is a Polymer Electrolyte Membrane (PEM) fuel cell powered bus that operates on hydrogen. The fuel cell has net power output of 150 kW and 80 kW of lithium ion power batteries (8 kWh) are used to balance the load. Two 75 kW electric motors that are capable of recuperative braking are used to power the wheels.

BEV-SR: Battery Electric Vehicle – Short Range. This is a battery electric bus powered by lithium ion batteries. This bus is assumed to have a range of only 12 km, but is assumed to regularly recharge its batteries along the route with inductive charging. The wheels are powered by two 75 kW electric motors that are capable of recuperative braking.

BEV-LR: Battery Electric Vehicle – Long Range. This is a battery electric bus powered by lithium ion batteries. This bus is assumed to have a range of 200 km, and is assumed to charge its batteries once per day. The wheels are powered by two 75 kW electric motors that are capable of recuperative braking.

In general, while modelling bus performance, we keep the basic parameters of all buses the same and include differences between buses only where they are due to differences in powertrains. A summary of the most important bus parameters for each powertrain type is shown in Table 1. Furthermore, the following sections discuss some of the most important aspects of the life cycle inventories for buses. Section 3.1 examines the modelling assumptions for batteries, wireless charging, fuel cells and hydrogen storage in more detail. Section 3.2 describes how we modelled bus energy consumption. Section 3.3 looks at the operating emissions from buses, while section 3.4 describes the energy chains used to refuel and recharge the buses.

Table 1 Summary of most important bus parameters

			ICEV-D	HEV-D	ICEV-CNG	FCEV	BEV-SR	BEV-LR
Bus mass	kg	2017	10890	10960	11110	11050	10720	12680
		2030	10730	10760	10890	10570	10330	11410
Maximum Range	km	2017	500	500	500	500	12	200
		2030	500	500	500	500	12	200
Traction energy demand	MJ/km	2017	5.3	3.9	5.3	4.4	4.4	4.7
		2030	4.8	3.5	4.8	3.9	3.9	4.0
Onboard energy storage	kWh	2017	2420	1800	2580	1480	86	380
		2030	2100	1570	2230	1230	75	325
Auxiliary Power	kW	2017	7.0	5.3	7.0	5.3	5.3	5.3
		2030	5.4	4.9	5.4	4.9	4.9	4.9
HVAC Power	kW	2017	5.3	5.3	5.3	8.5	8.5	8.5
		2030	4.1	4.1	4.1	6.6	6.6	6.6
Tank to Wheel Efficiency	%	2017	29.0	30.0	27.5	41.6	85.0	85.0
		2030	30.2	31.2	28.6	43.9	85.6	85.6
Charging efficiency	%	2017	-	-	-	-	85	90
		2030	-	-	-	-	85	90
Recuperation efficiency	%	2017	-	50	-	50	50	50
		2030	-	53	-	53	53	53
Total energy consumption	MJ/km	2017	17.5	12.9	18.6	10.6	5.1	5.5
		2030	15.1	11.3	16.0	8.9	4.5	4.7

3.1 Batteries, induction chargers, fuel cells and hydrogen tanks

Energy batteries are modelled to be lithium ion batteries with a current energy density of 150 Wh/kg, assumed to improve to 250 Wh/km in 2030 [6]. LCI data for lithium ion batteries is taken from ecoinvent on a per kilogram basis. Batteries are assumed to be liquid cooled for BEV in order to extend their lifetime. Batteries are assumed to be replaced once during the bus lifetime for current buses and not at all for 2030 buses [7]. Power batteries are modelled to be the same lithium ion batteries as used for energy storage. We assume a maximum discharge rate of 10 C to define the power capabilities of batteries.

Short range battery buses are charged by induction charging. Life cycle inventories for the inductive charging units are taken from Bi, De Kleine [8]. We reduce the efficiency of charging for short range electric buses from 90% to 85% to account for the speed of charging and losses in the inductive charging system.

Hydrogen tanks are made of an aluminium cylinder wrapped with carbon fiber with stainless steel connections. Hydrogen tanks are assumed to have a mass storage efficiency of 5%, increasing to 7% in 2030 [9].

Fuel cells are assumed to be Polymer Electrolyte Membrane (PEM) type. We take the basic fuel cell model from Simons and Bauer [10], using the 2020 fuel cell as the 2017 base case for performance and manufacturing. However, as heavy duty fuel cells are typically operated to optimize lifetime, we decrease the power density from 800 mW/cm^2 to 600 mW/cm^2 for 2017 models. For 2030 the power density is set to 800 mW/cm^2 which represents expected improvements in power density and catalyst loading, the two parameters that have the most influence on the environmental impacts of fuel cell production. Furthermore, average fuel cell system efficiency (LHV) is increased from 49% in 2017 to 54% in 2030. The fuel cell stack is assumed to be replaced twice for 2017 buses, and only once for 2030 buses [11].

3.2 Bus Energy Consumption

Operating energy consumption is determined by modelling each bus driving the urban section of the World Harmonized Vehicle Cycle (WHVC) for heavy duty vehicles [12]. We calculate the instantaneous power at each second of the WHVC required for the bus to follow the pre-determined velocity versus time profile. This includes the power requirements to overcome rolling and aerodynamic resistance, acceleration/ deceleration, auxiliary power and heating and cooling demands, which are all calculated using typical values for urban buses. Bus mass is determined by the model by summing the mass of the bus glider and powertrain with the mass of the energy storage system, which is calculated iteratively with energy consumption considering the required range of the bus. For average operation we consider that the air conditioner is running 25% of the time and the heater 15% of the time. Auxiliaries are assumed to be slightly more efficient for electric powertrains compared to combustion powertrains, which often use less efficient pneumatic systems. Input values for auxiliary consumption are from Andersson [13]. Figure 1 shows a sample result of the power demand for a 2017 long range battery electric bus.

Integrating the power demand over the driving cycle and dividing by the total distance travelled yields energy consumption per kilometre travelled. We use average efficiencies for all powertrain components, such as engines, motors, transmissions etc. to calculate tank to wheel efficiency for each powertrain (see Figure 2).

We choose to model the energy consumption of buses instead of directly taking real world data. The reason for this is that the modelling approach allows us to consider individual improvements to buses over time, such as improved fuel cell stack efficiency, or use of heat pumps to reduce heating energy demand, while this is not possible when directly using real world measured data. Furthermore, the method allows consistent comparison for different bus powertrain types as all other variables, such as driving cycle and auxiliary power demand may be held constant. We calibrate model results with real world data found in the literature and manufacturer claims and find that the current model results fit very well with current bus performance for all powertrain types.

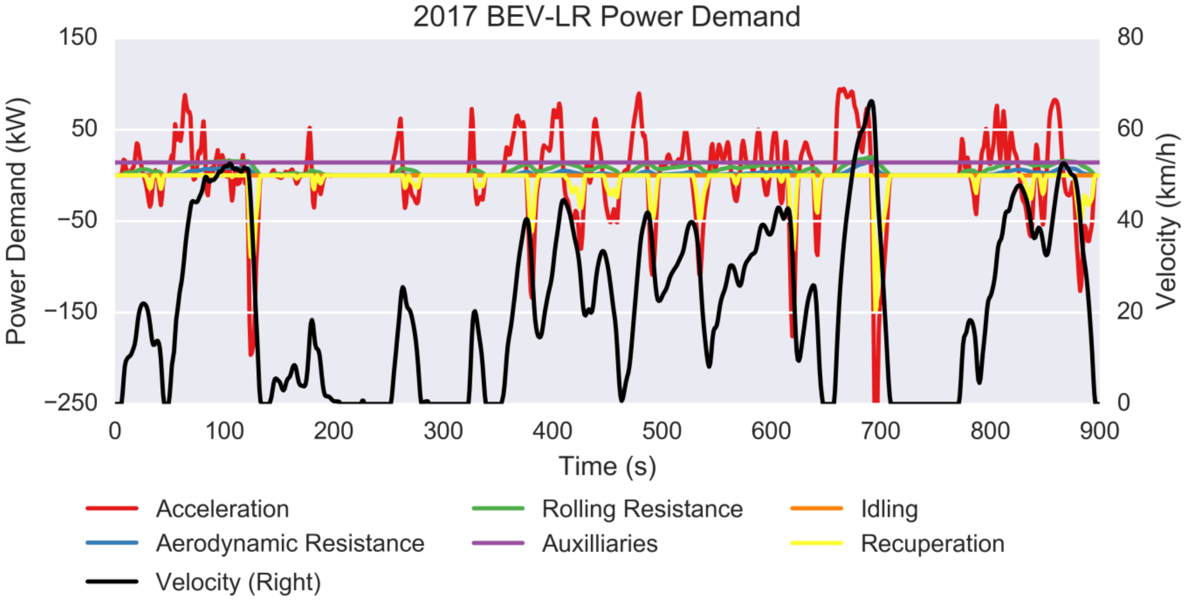

Figure 1: 2017 Sample bus power demand while driving the WHVC Urban driving cycle.

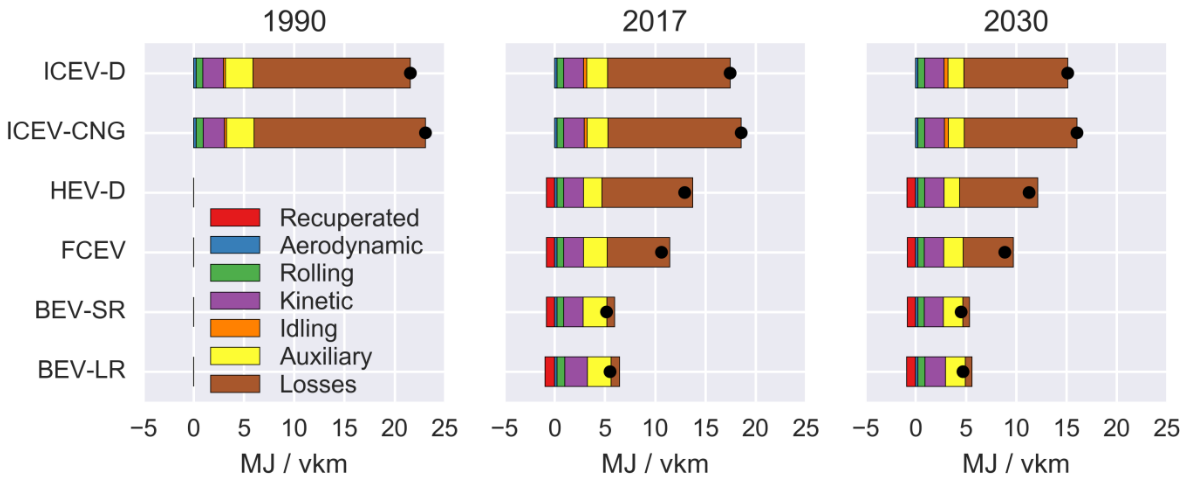

Figure 2: Tank to wheel energy consumption per vehicle kilometer for 12 m urban buses produced in 1990, 2017, and 2030.

3.3 Bus Operating Emissions

We calculate exhaust emissions for diesel and natural gas buses on the basis of emissions per kWh of energy consumed, which is also how the European heavy duty vehicle emissions regulations are defined. The reason that we make this distinction is because it allows us to better consider the emissions of vehicles that aren't yet included in the emissions databases such as hybrid buses or buses of different sizes, or to include the impacts of different air conditioning load scenarios.

Emissions values are taken from the EMEP 2013 [14] and the HBEFA version 3.2 [15], and converted to emissions per kWh of consumed energy. We make the simple assumption that emissions per unit energy in 2030 are the same as in 2017. However, because future buses are modelled to have lower energy consumption, the emissions per kilometre travelled will also decrease in the future.

We further consider particle emissions due to tire, brake and the road wear from the EMEP 2013 [14]. Buses with regenerative braking are assumed to have reduced brake wear particle emissions.

3.4 Energy Chains

Although the model includes a wide variety of energy chains, for the purpose of brevity we limit results to the most relevant energy chains for this paper.

Electricity production is considered to be from natural gas combined cycle plants and onshore wind turbines operating in Germany. Hydrogen is produced by either electrolysis with the above electricity sources or steam reforming of methane (SMR). Electricity datasets are taken directly from ecoinvent. Hydrogen production datasets are taken from Simons and Bauer [16], but efficiency values are updated based on the most recent and future values listed by the US Department of Energy [17].

4 Results and Discussion

Results are presented for global warming potential (Figure 3) and particulate matter formation potential (Figure 4) for 12 m buses. We compare 2017 and 2030 buses, but also include results for ICEV buses produced in 1990 to give a better understanding of how the environmental impacts of buses have changed over time.

When renewable energy is available, in this case wind electricity, battery electric vehicles have excellent potential to reduce the global warming impacts of urban buses. We find that short range opportunity charge buses have the best environmental performance due to reduced battery manufacturing impacts as well as efficiency gains due to weight reductions. If opportunity charging is not feasible, long range electric buses also show excellent performance. Fuel cell buses charged with renewable energy still have excellent performance in terms of global warming, and are essentially free from the range concerns that faced by battery electric buses.

If the source of primary energy is natural gas, battery electric buses still offer climate benefits compared to combustion engine buses, though fuel cells do not. When diesel is the fuel source, hybrids are found to always outperform conventional diesel buses. Significant improvement is expected in the environmental performance of all bus powertrain types by 2030, though the ranking of technology performance remains the same.

In terms of particulate matter formation potential, the most obvious result is that direct emissions from combustion buses have been drastically reduced since 1990. Current conventional buses actually perform very well in this category compared to battery and fuel cell buses. The reason that fuel cell buses perform comparatively poorly in this category is due to the upstream emissions in the energy chain. For hydrogen from SMR, this is due to the emissions in the methane production chain. For hydrogen from electrolysis this is due to the large amount of nickel used in the electrolyzer, as SO_x emissions from nickel smelting are quite high. It is important to note that LCA does not account for the location of emissions and that upstream emissions, which may take place far from humans, are counted equally as direct tailpipe emissions that are emitted in city centers. Thus, the only conclusions we can reasonably draw from these results are that current combustion buses have greatly reduced their urban air pollution contributions compared to older buses, though the emissions are still not zero. Conversely, battery and fuel cell buses do have nearly zero direct emissions, though their upstream emissions are similar or even higher than those of combustion buses.

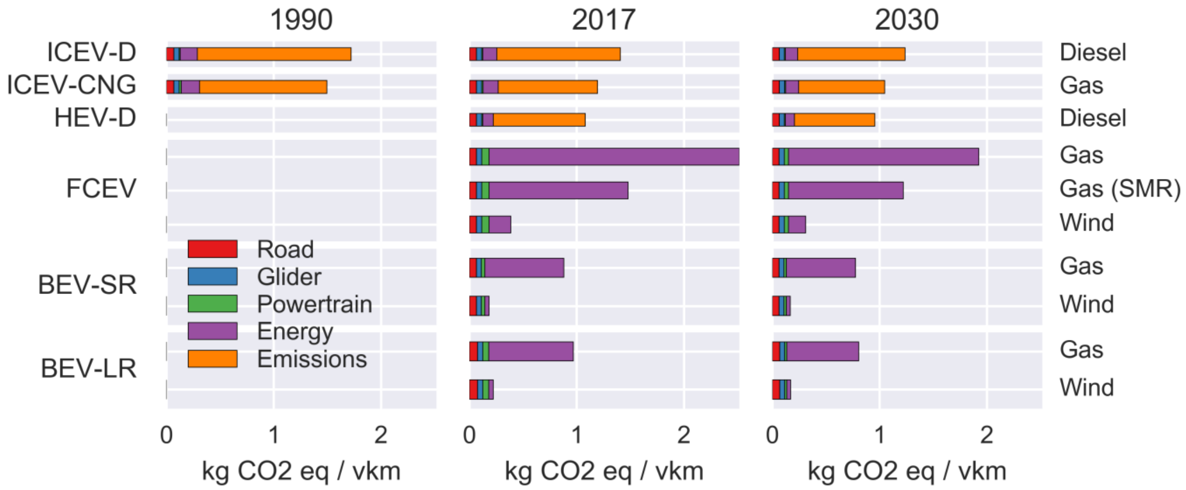

Figure 3: Global warming potential results for 12 m urban buses produced in 1990, 2017, and 2030.

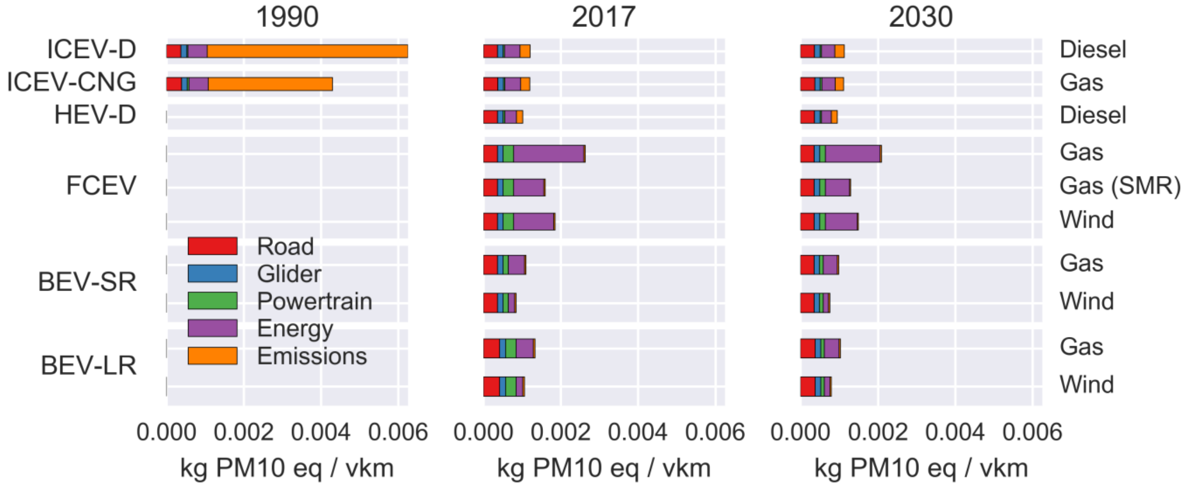

Figure 4 Particulate matter formation potential results for 12 m urban buses produced in 1990, 2017, and 2030.

5 Conclusions

In this work we compare the life cycle environmental impacts of past, current and next generation urban buses. We considered all likely powertrain combinations including combustion, hybrid, fuel cell and battery electric buses as well as a variety of different primary energy sources. Based on this detailed analysis of urban buses, we conclude that battery electric buses have the best environmental performance in nearly all environmental impact categories, for nearly all primary energy carriers. However, battery electric buses are not suitable for some bus routes due to range restrictions or the inability to install fast charging stations on route. In these cases, fuel cell buses are also a good choice as they have good performance in nearly all environmental impact categories – so long as a renewable source of hydrogen is available. When this is not the case, hybrid electric buses are preferable, especially if they have sufficient energy storage capacity to operate in all electric mode in city centers.

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