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Report on the EBRT reference concepts and EBRT eco-system

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ACRONYMS

BRT: Bus Rapid Transit

CMS: Charging Management System

CS: Charging Strategy

DSO: Distribution System Operator (for electricity distribution)

EC: European Commission

EMS: Energy Management System

HVAC: Heating, Ventilation, and Air Conditioning

IMC: In-motion Charger

KPI: Key Performance indicators

LCA: Lifecycle Analysis

LCC: Life Cycle Cost

PT: Public Transport

PTA: Public Transport Authority

PTO: Public Transport Operator

RBS: Regenerative Braking System

TCO: Total Cost of Ownership

TMS: Thermal Management System

UC: Use Case

WP: Work Package

ZEB: Zero Emission Bus

1 EXECUTIVE SUMMARY

eBRT2030 is a 4-year Horizon Europe project that develops innovative solutions for future zero-emission rapid transit for public transport. The project aims to support the next generation of innovative and effective public transport by demonstrating real-life electric Bus Rapid Transport (eBRT) concepts with fully electric buses in cities of Europe and partnering countries.

This document is a Report on the EBRT reference concepts and EBRT eco-system (D3.3), in the frame of WP3 – "Multi-level design & planning tool and Development of Innovative EBRT technologies".

This report builds upon D3.1 using the eBRT simulation framework to define the eBRT reference concepts. The reference concepts cover the different innovative project technologies such as vehicle-to-grid charging, improved thermal models, dynamic speed and passenger models, etc. so that a wide variety of scenarios can be considered. A library has been built with these models to be seamlessly used and interfaced with the main design and planning tool. This framework is then used to verify the results in various operating conditions and scenarios using the project use cases in five of the six European cities: Barcelona (ES), Amsterdam (NL), Athens (GR), Prague (CZ) and Rimini (IT). Results are presented and discussed regarding the reference eBRT concepts and technologies developed on the project. In addition, the achieved results have been reviewed in consultation with partners from the demo cities to validate the platform.

2 INTRODUCTION

The eBRT2030 project is a Horizon Europe Innovation Action that aims to create a new generation of advanced full electric, urban and peri-urban European Bus Rapid Transit (BRT) enhanced with novel automation and connectivity functionalities, to support sustainable urban transport by reducing cost/km/passenger, total cost of ownership (TCO), greenhouse gases (GHG) and pollutant emissions and traffic congestion. The project involves public transport authorities and operators, vehicle and infrastructure manufacturers, research and innovation organisations and city networks.

2.1 PURPOSE OF THE DELIVERABLE

This deliverable builds upon the eBRT simulation platform in D3.1 for the definition of a reference eBRT system (T3.2). This reference eBRT aims to cover a wide variety of use cases, with different driving scenarios, variations in passenger loading, road inclination, driving speed, etc. This is covered by the different innovative project technologies detailed in the simulation framework buildup in D3.1 (incl. thermal models, LCA and TCO models, data-driven battery model, etc.). In addition to that, energy management strategies such as eco-comfort, eco-driving and eco-charging are also applied to the simulation platform and results are discussed.

This report also presents the verification of the reference eBRT concept for the EU project demonstrations, as well as a real eBRT line operated in Nantes. Therefore, the different use cases have been characterized with the collection of relevant data and specifications. Then, results are presented for five use cases of the project, which cover a wide variety of scenarios: Barcelona (ES), Amsterdam (NL), Athens (GR), Prague (CZ) and Rimini (IT).

2.1 STRUCTURE OF THE REPORT

The simulation framework is first described as a summary of D3.1 in order to set the main characteristics of the tool. Next, the energy management strategies which can be applied to eBRT scenarios are defined, with eco-comfort, eco-charging and eco-driving.

The six considered scenarios (including Nantes as a baseline use case) are described based on specifications and data coming from the project demonstration leaders. This is then used to present and discuss the results for the simulation of the different use cases and linked innovations, also assessing the application of the energy management strategies.

3 EBRT2030 SIMULATION FRAMEWORK

The Simulation Framework is an analytical tool developed in MATLAB/Simulink environment in previous projects (for example, ORCA for the hybrid electric truck, ASSURED for battery electric buses and battery electric trucks) to simulate the energy requirements of fleets of heavy-duty electric vehicles when subjected to a Use Case (UC) scenario. These energy requirements can be used to quickly size the electric vehicle powertrain (including the battery, the DC/DC converter, the electric motor system, and gearbox) to their optimum power rating needed to execute a given scenario. In EBRT2030, the simulation framework has been significantly upgraded to capture the technological innovations from the project, including G2V and V2G, modular charging concept, battery backup for peak shaving, LCA and extended TCO analysis, improved cabin thermal model and battery thermal model, and realistic passenger and speed model as a function of time of day and route location. These improvements are highlighted in extensive detail in deliverable report D3.1. The Simulation Framework can be used by the public transport operator (PTO) to determine the total cost of ownership (TCO) to invest in the electrical infrastructure and the vehicle fleet in a particular route. The Simulation Framework can also be used by the distribution system operator (DSO) to determine the load on the electricity grid throughout the day due to fleet charging requirements. Finally, the Simulation Framework can be used to analyze the reduction in the energy and charging requirements when various energy, thermal, and charging management strategies (i.e., ECO-strategies) are applied. The framework is extensively described in D3.1 “Planning and EBRT simulator tool” and the main highlights are provided here.

3.1 DESCRIPTION OF THE ELECTRIC BUS POWERTRAIN MODEL

The electric bus powertrain comprises the traction system, the auxiliary system, the control and energy management system, and the charging system as shown in Figure 1.

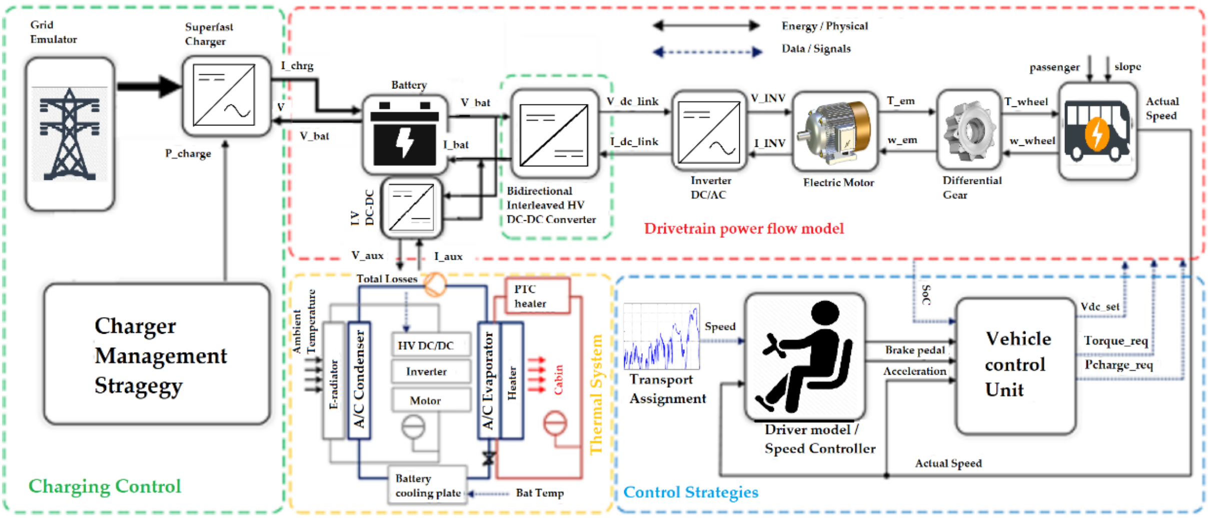

Figure 1. Electric bus powertrain and charging architecture.

The vehicle powertrain developed in the simulation framework consists of the two major systems, namely the traction system and the auxiliary system. The traction system includes the vehicle chassis, the Gearbox, the Electric Motor (EM), the Inverter, and the high-power bidirectional DC/DC converter. The auxiliary system consists of the cabin climate control, battery cooling, the heating, ventilation and air conditioning (HVAC) system, and the low-power unidirectional DC/DC converter. Linking the traction and the auxiliary system is the energy storage system (ESS). There is also the control system that supervises the functionality of the various powertrain components through control commands, e.g., the traction system is controlled by the torque command given to the EM and the braking commands given to the brakes, while the auxiliary system is controlled by the cabin reference setpoint temperatures and the battery cooling and heating threshold temperatures given to the HVAC system. The control system also consists of the energy management system (EMS), the thermal management system (TMS), and the charging management system (CMS), and implements the various energy saving strategies including ECO-charging, ECO-comfort, and ECO-driving. The charging system exists outside of the vehicle powertrain and consists of DC chargers (for opportunity, in-motion, and overnight charging) and the substation transformer. These systems are explained in more detail in Deliverable report D3.1 report describing the eBRT2030 Simulation Framework.

3.2 BASELINE FUNCTIONALITIES OF THE SIMULATION FRAMEWORK

The Simulation Framework provides various features that are of use to the user, including:

1. Scenario creation
    a. Route definition (route distance, average route speed, driving cycle selection, and elevation profile)
    b. Climate definition (temperature variation throughout the day, humidity, wind speed, solar radiation, estimate of cloud cover)
    c. A passenger profile in the bus that randomly changes at every bus stop
    d. Charging scenario (opportunity and depot charging, charging duration and power)
    e. Fleet design (number of buses required in route, peak bus frequency)
2. Energy requirement (in kWh/km)
3. Basic TCO (in €/km) and LCA (in kg/km of COx, NOx, PMx)
4. Grid electricity consumption profile (kW) and total electricity consumed per day (in kWh)
5. Various output plots, including speed profile, battery profile (SoC, power, voltage, current, temperature), torque profile (reference vs. actual), braking profile, and weather profile
6. Energy management strategy implementation: ECO-charging, ECO-comfort, and ECO-driving.
7. Scalability and flexible sizing of the power requirements of the electric powertrain components (battery capacity sizing, electric motor sizing, dc/dc converter sizing)
8. Fleet charging optimization and charge scheduling

3.3 EXTENDED FUNCTIONALITIES OF THE SIMULATION FRAMEWORK

The extended functionality describes the extra features that have been added as part of the eBRT2030 project, including:

1. Vehicle to Grid charging model
2. Dynamic passenger model
3. Dynamic speed model
4. Modular charging model
5. Battery backup model
6. In-motion charging model

7. Cabin thermal model
8. Extended TCO features
9. LCA model
10. Data-driven battery model
11. Multi-layer fleet design model

These extended functionalities are explained in more detail in Deliverable D3.1 describing the eBRT2030 Simulation Framework and linked tasks/deliverables (D3.2, D3.4).

3.4 SIMULATION REQUIREMENTS

The eBRT2030 components library has been created in MATLAB version r2023b; therefore, it will run on that or later versions of MATLAB, but not earlier versions. Furthermore, to ensure proper build of the simulation models before simulation, the required data files (.mat), the simulation model files (.slx), and the protected libraries (.mexw64 and .slxp), as well as the inputs required for UC simulation should be present in the simulation folder. The full descriptions of these are given in deliverable D3.1.

4 ENERGY MANAGEMENT STRATEGIES

According to powertrain simulations [1], in an electric bus, the losses in electric motors account for approximately 40% of all losses in the electric powertrain, followed by the ESS, which accounts for another 25% (18m buses) to 30% (12m buses) of the losses in the electric powertrain [1]. Thus, improvement to the performance of the traction system and the charging system will result in significant energy savings. Moreover, powertrain simulations also show that the auxiliary system consumes between 25% and 50% of the total energy for 18m buses, and between 20% to 30% of the total energy for 24m buses, depending on the season, according to the Use Case simulation results. Therefore, addressing the auxiliary energy requirement will also result in significant savings throughout the year. To realize these energy savings, it is important to understand and therefore optimize the energy management (ECO-driving), thermal management (ECO-comfort), and charging management (ECO-charging) systems in the buses. These "ECO" features are energy saving techniques are developed to help electric buses (e-buses) reduce their considerable energy requirements, so that they can cover greater range using the same energy content of their ESS, i.e., extend their operational range, and thus save costs resulting in a lower TCO.

4.1 ECO-COMFORT

The more the target cabin temperature deviates from ambient temperature, the more energy is needed from the bus's HVAC system. Thus, reducing the temperature deviation (lower cabin temperature during cold days, higher during hot days) reduces the energy consumption of electric buses and increases the battery capacity share that can be used for traction, directly increasing the driving range. However, reducing the temperature deviation to lower energy consumption usually has an adverse effect on passenger comfort, and should be carefully appraised.

Using the low-fidelity cabin thermal model (described in D3.1 and D3.4), cold day scenarios can be compared, where the target cabin temperature is lowered to see the effects on energy consumption. To do this comparison an artificial example data set of a cold day with eight hours of operation is used with two peak periods of two hours each, and half an hour of transit between bus line and depot with an hour of pre-heating before start (see Table 1).

Table 1: Example data set for a sample scenario.

	Number of passengers	Ambient temperature	Solar radiation	Heat pump max power	PTC max power	Waste heat power
1h pre-cond.	0	-10 °C	0 %	20 kW	40 kW	5 kW
0,5h transit	0	-10 °C	0 %			7,5 kW
1h	40	-10 °C	0 %			10 kW
2h peak	80	-10 °C	30 %			10 kW
2h	40	-10 °C…-5 °C	60 %			10 kW
2h peak	80	-5 °C	60 %			10 kW
1h	40	-5 °C	30 %			10 kW
0,5h transit	0	-5 °C	30 %			7,5 kW

In both scenarios the pre-heating is done to a target cabin temperature of 18 °C with the baseline scenario operating with a target cabin temperature of 18 °C and the lowered cabin temperature scenario operating with a target cabin temperature of 16 °C. Table 2 shows that the scenario with the lowered cabin temperature consumes almost 26 kWh less energy (-19,2 %) compared to the baseline. In this comparison the reduction in passenger comfort was not evaluated, but should be carefully considered, as the gains from HVAC energy consumption reduction are significant.

Table 2: Energy consumption of HVAC for the assumed scenario

Scenario	Pre-cond. heat pump	Pre-cond. PTC	Pre-cond. total	Operation heat pump	Operation PTC	Operation total
Baseline	12,3 kWh	28 kWh	40,3 kWh	9,6 kWh	125,1 kWh	134,7 kWh
Lowered cabin temperature	12,3 kWh	28 kWh	40,3 kWh	4,8 kWh	104,0 kWh	108,8 kWh

4.2 ECO-CHARGING

ECO-charging is an energy saving technique that can be used during battery charging to reduce the battery cooling energy expenditure using either low-power charging or pulsed charging instead of continuous charging for high-power charging.

Table 3 shows the simulation results of the charging efficiency of a 7.2V, 72Ah lithium nickel-manganese-cobalt (Li-NMC) battery module when it is charged continuously, at different charging rates (C-rates), until its state of charge (SoC) has reached 90% starting from 20%; thus, the total energy accumulated by the module during charging is 415Wh. It is observed that the losses are severe at the higher C-rates with a significantly reduced charging efficiency, which manifests as heat, which then requires further expenditure of energy to keep the battery cool. This results in a charging efficiency of only 66% at 2.5C for a Li-NMC cell [2]. The increased losses incurred during high C-rate charging are resistive losses, which quadruple with every doubling of the charging current. It is also for this reason that doubling the charging rate does not result in the halving of the required charging duration. Furthermore, the high temperatures experienced by the module charging at these extreme C-rates results in significant reduction in its lifetime [3].

Table 3. Energy requirements of charging of a 7.2V, 72Ah Li-NMC battery module with 415Wh (continuous charging).

C-rate	Losses	Cooling	Charge	Efficiency	Duration
0.5	12Wh	36Wh	467Wh	88.4%	6004s
1.0	23Wh	41Wh	485Wh	83.1%	3347s
1.5	34Wh	60Wh	512Wh	76.7%	2471s
2.0	44Wh	77Wh	535Wh	71.0%	2049s
2.5	54Wh	93Wh	554Wh	66.4%	1798s

Table 4. Energy requirements of charging of a 7.2V, 72Ah Li-NMC battery module with 415Wh (pulsed charging).

C-rate	Period	Pulse	Loss	Cooling	Charge	Duration	Efficiency
0.5	10s	48%	9Wh	24Wh	452Wh	11744s	91.1%
1.0	10s	25%	16Wh	36Wh	472Wh	11503s	86.3%
1.5	10s	16%	22Wh	45Wh	486Wh	11835s	82.9%
2.0	10s	12%	28Wh	48Wh	492Wh	11795s	81.4%
2.5	10s	10%	34Wh	50Wh	496Wh	11305s	80.5%

Table 4 shows the application of optimal pulse configurations for the different charging C-rates of the Li-NMC 7.2V, 72Ah battery module. It is observed that pulse charging results in significant improvements in the charging efficiency, especially at higher charging C-rates. While 0.5C charging experiences barely 3% improvement in charging efficiency, the highest charging C-rate (2.5C) experiences up to 14% improvement in charging efficiency. That is a reduction of 58Wh in extra charging energy required during superfast charging. Since low c-rate charging is already efficient, there is less scope for further improvements to the efficiency using pulse charging. Thus, there is no need for implementing ECO-charging into low-powered overnight chargers, whereas it is desirable to implement ECO-charging in high-powered opportunity chargers as it will lower the charging energy needed, improve the lifetime of the battery, and put less stress on the electricity grid. However, the downside to pulsed CS is that it requires a much larger charging duration to allow the battery to get fully charged. This is problematic regarding the busy schedules for public transport buses and delivery trucks that do not allow for large charging breaks. Therefore, ECO-charging also relies on minimizing the use of the opportunity charging and maximizing the utilization of the low-power overnight charger in the depot as shown in Figure 2.

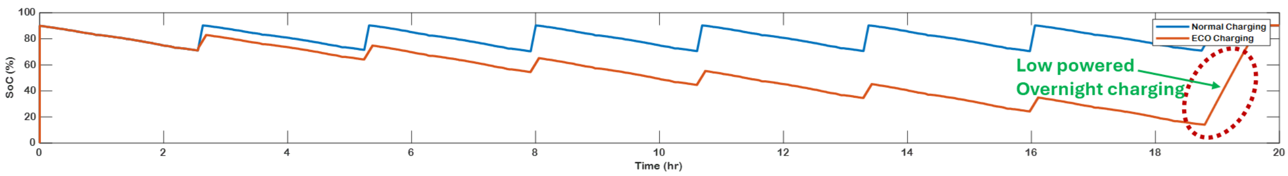

Figure 2. Daily battery SoC profile as a result of Eco-charging.

The duration of the duty cycle of the charging pulses in the opportunity charger is optimized during ECO-charging such that the battery receives slightly less charge (compared to normal mode charging) in each opportunity charging session; this ensures that the battery's SoC drops to its lowest allowable value (set by the battery OEM/bus operator) by the end of the operational day. Since the bus enters the depot with its battery *operationally* depleted, this results in maximizing the time that the bus spends charging its battery in the depot, where the low-power charger can more efficiently charge the battery. The ECO-charging algorithm ensures that the SoC of the battery does not drop below the *operational* and *safety* threshold set by the OEM and the PTA at any time during the bus's operating hours; thus, it is entirely feasible to employ ECO-charging without affecting the battery's capability to fulfil the operational needs of the bus route. When dealing with bus fleets, ECO-charging is also helpful to the electricity grid since using pulsed charging reduces the ***average load*** on the electricity grid as shown in Figure 3.

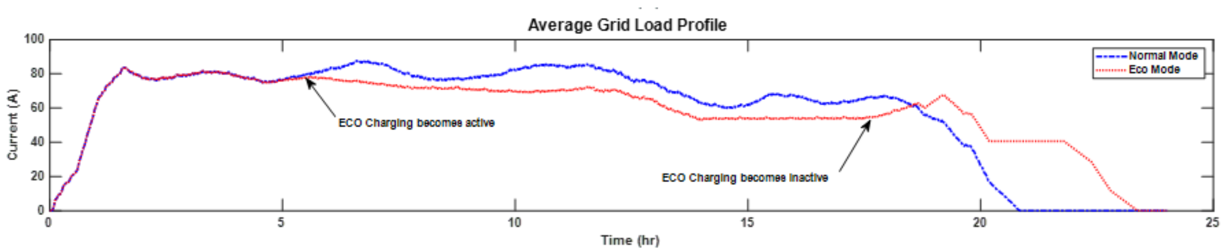

Figure 3. Average load on the electricity grid due to application of ECO-charging with electric bus fleets.

Furthermore, multiple chargers implementing pulsed charging via ECO-charging can implement "active synchronization", where the charger can phase-shift their charging times so that the charging pulse of one charger falls in the pause time of the other charger, thus reducing the ***peak load*** in the grid as shown in Figure 4. It should be noted that the charging strategy in Figure 4 only relates to static charging, which is mostly in constant current mode, not to in-motion charging, whose charging current profile is more dynamic and bi-directional.

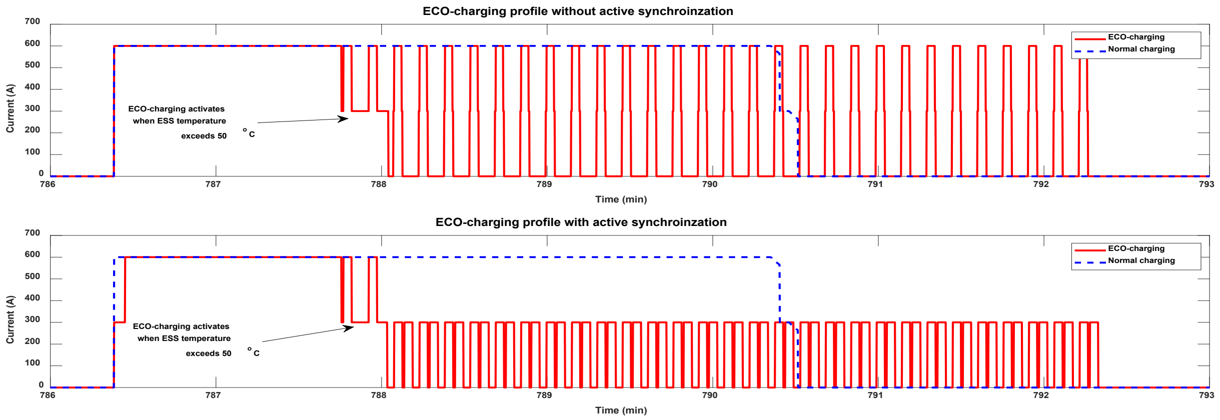

Figure 4. Active synchronization between multiple chargers implementing ECO-charging.

4.3 ECO-DRIVING

The aim of ECO-driving is to present a multi-objective energy management strategy for electric heavy-duty vehicles, such as buses and trucks, to minimize the energy consumption, the operational cost, and improve driving range. ECO-driving capability was achieved via two approaches: first through the modification of the driving profile into an "eco-friendlier" one and through optimally actuating the EM to meet that speed profile. The common thread in ECO-driving from previous research is the modification of the driving style, which, from a simulation perspective, can be thought of as a modification of the standard driving cycle to an "eco-friendly" version as shown in Figure 5.

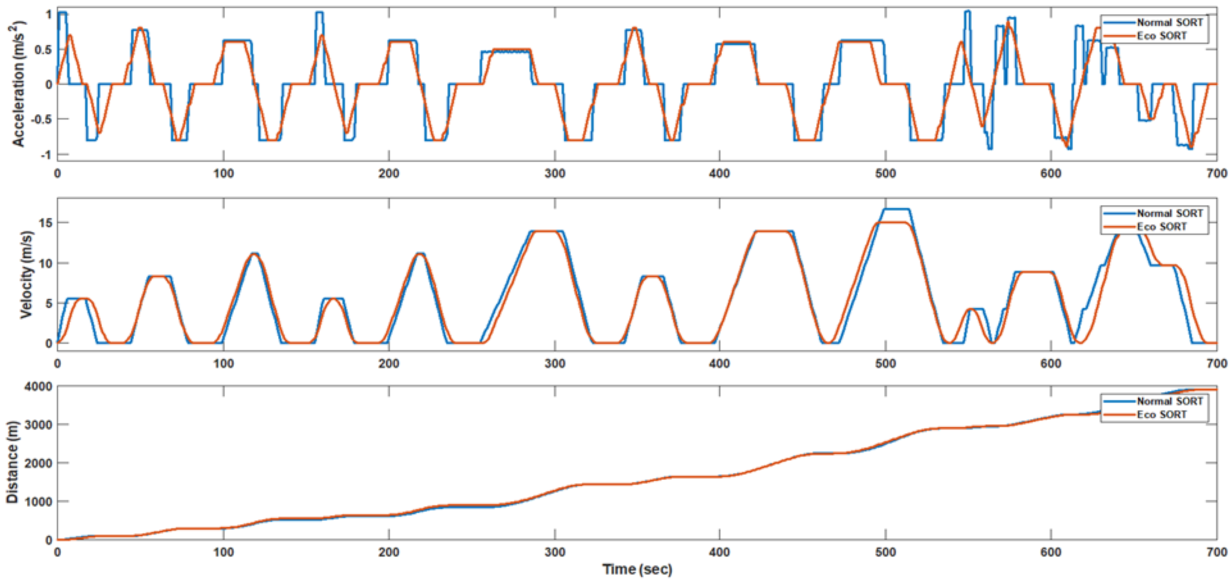

Figure 5. The Hybrid-SORT driving profile converted to its Eco-friendly version using ramped acceleration method to ensure smoother changes in velocity.

The ECO-driving algorithm relies more on ramped acceleration instead of step acceleration to ensure smoother changes in velocity. Furthermore, the ECO-driving algorithm limits acceleration of heavy-duty vehicles to +/-1m/s^2, and the vehicle's top speed to 54km/h in urban areas and 72km/h on highways. Finally, the ECO-driving algorithm improves the energy efficiency of the vehicle by optimizing the regenerative braking system (RBS), through actuation of the EM in various modes during the braking process [4]; depending on specific situation, a given mode of actuation performs better than others. Thus, the best method to recover the maximum energy from regenerative braking involves a heuristic process to tune the mode of actuation depending on the 1) current velocity of the vehicle, 2) the desired deceleration, and 3) the grade of the road.

5 USE CASES DESCRIPTION

In this chapter the project use cases considered to address a wide variety of scenarios are described, based on the information provided by the partners, covering different driving routes, variations in passenger loading, road inclination, driving speed, etc. This is the starting point of the simulation results presented in the following chapter.

Among the project use cases, Amsterdam (NL), Athens (GR), Barcelona (ES), Prague (CZ) and Rimini (IT) are selected to verify the simulation platform and project innovations. In addition to that, a baseline eBRT scenario in Nantes is considered as proposed in the Grant Agreement. Nantes has an operational eBRT line since 2019; thus, it can provide baseline data for the energy requirements to compare with the UC scenarios. In task T2.1 (WP2) SEMITAN performed the characterization of the current eBRT system in Nantes in collaboration with the PTA, while in this task (T3.2), they supported in defining the reference eBRT and provided real-world data from the operated eBRT line in Nantes.

5.1 BASELINE

The baseline scenario is from Nantes, France, operated by SEMITAN, where there is an operational eBRT line that runs between Porte de Vertou and Foch Cathedrale. The line consists of 15 bus stops (including the end points) along the route, which is 7km in length. During peak hours the line is supported by 18 buses in operation, with a frequency of 3 minutes between buses. The buses operate for 19hr throughout the day and transport on average 42k passengers daily. Based on this description, it is estimated that each bus makes, on average, 21 trips per day; therefore, each bus has a daily operational distance of 294km or an annual operational distance of 100k km. The buses are 24m double articulated electric bus, with a maximum passenger capacity of 150 people, a battery capacity of 128.6kWh, and a curb weight of 25.37T. The bus uses 150kW electric motors to provide traction and has a 50kW auxiliary system, of which 26kW are dedicated to cabin climate control and the rest are overhead.

The route consists of 12x 600kW opportunity chargers along various points in the route, including 2 at Foch Cathedrale endpoint, 2 at Beaulieu, 2 at Generaie, 4 at Porte de Vertou, and 2 at the bus depot. The main aspect of the route is that it is a BRT line with infrastructure dedicated to performance, so 95% of the lanes are reserved for the buses with priority at all crossroads. This ensures that the driving profile of the bus is that of a highway driving profile, with constant speeds over long periods of time and subject only to the speed limits at different sections of the route as shown in Figure 6.

The climate of Nantes is temperate suboceanic with mild weather ranging from winter temperatures of 3 °C to 9 °C to summer temperatures of 14 °C to 25 °C. There is constant rainfall throughout the year with winters having greater rainfall of an average of 92mm over 12 days per month and summer having lower rainfall of an average of 44mm over 6 days per month. The daylight ranges from 8.5hrs during winter to 16hrs during summer.

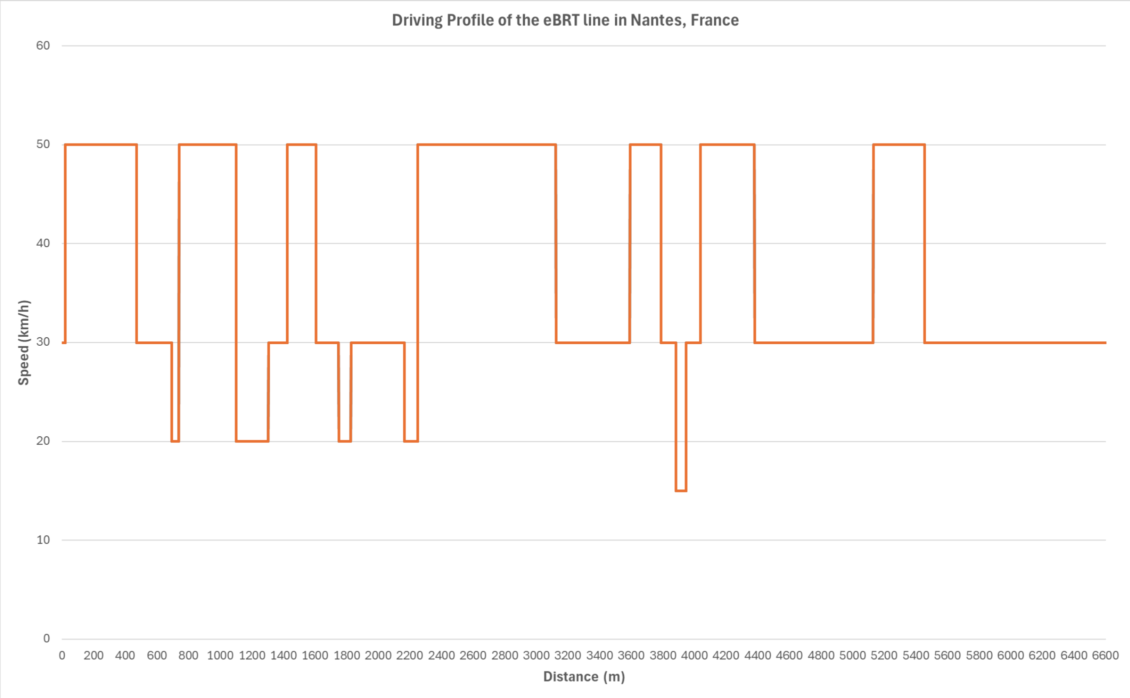

Figure 6. Route speed limits along the eBRT line in Nantes, France.

5.2 AMSTERDAM

The Amsterdam UC scenario consists of the e-BRT Line-300, which connects the suburbs of Amsterdam, Bijlmer, via Amsterdam Schiphol Airport to Haarlem Central Station. E-BRT Line-300 has both suburban and interurban characteristics. The PTA Connexxion operates a high-frequency 24/7 BRT system along the 40.5km long route of Line-300, primarily on dedicated bus infrastructure used by commuters as well as tourists. Approximately 340 bus trips (or 170 return trips) are scheduled daily on Line-300, shared between 32 buses, with individual buses each travelling approximately 385km within the daily operational window of 20h.

Due to the transition to electrical propulsion, the demand for electric energy for fleet charging is increasing excessively in the Netherlands and the power grid facilitating the demand is reaching its limits. Therefore, network providers cannot deliver the required grid connection and capacity to support the eBRT operation at preferred locations under normal operating conditions. On the other hand, mitigation by implementing charging infrastructure on locations where an adequate grid connection is available, is resulting in less-than-ideal charging locations with operational drawbacks and limitations to the further development of the eBRT network. This lack of grid capacity is slowing down the transition to electric bus fleets. To mitigate this lack in charging capacity, the Use Case focuses on grid reinforcement through the integration of a large-scale stationary battery buffer system with bidirectional functionality for high power charging and achieve peak shaving of load in the grid.

The climate of Amsterdam is temperate oceanic and strongly influenced by its proximity to the North Sea. It has mild and cool weather with temperatures ranging from 0 °C to 6 °C during winter to 13 °C to 22 °C during summer. Amsterdam enjoys rainfall throughout the year; however, the rainy season with heavy rainfall is during Autumn with 85mm of rainfall over 13 days and light rainfall during Spring with 40mm of rainfall over 6 days. The daylight ranges from 8hrs during winter to 16.5hrs during summer.

5.3 ATHENS

The Athens UC scenario envisions deployment of the eBRT service in the Syggrou corridor, a major urban freeway of 4 km length with right-of-way of 3-4 lanes per direction (with a median), connecting the Athens central business district and the Athens seaside. It is a high-demand transportation corridor (with several attractors) currently devoted in full to private transport. The eBRT line connects the Syggrou Fix metro station in the Athens downtown area to the Stavros Niarchos cultural center, next to the Athens coastline (Athens Riviera), and will have a length of 4.9 km per direction. The line will operate along Syggrou corridor, a four-lane urban freeway. The route consists of 15 stops and takes 20 minutes to go from one end to the other during peak hour traffic, when the mean speed is the lowest.

The line is served by 2x 18m, 19-ton e-buses powered by 520kWh batteries and 370kW electric motors. The trolley catenary can supply a charging power of 350kW for opportunity charging. The buses arrive with a frequency of 25 minutes between buses during peak hour to 40 minutes between buses during other times. The operational duration of the route is 19h per day, during which time the buses make, on average, 28 return trips. Thus, each bus travels 100k km annually.

The concept with this UC is a hybrid concept where the trolleybus catenary (for bus #10) is used for opportunity charging utilizing on-board chargers and pantographs. Athens has a hot Mediterranean climate with hot summers and mild winters. The temperatures range from 8 °C to 13 °C during winter and from 23 °C to 32 °C during summer. The rainfall in Athens is practically non-existent during the summer months and occurs mainly during winter, reaching a maximum of 63mm of rainfall over 6 days. Athens enjoys 9.5hrs of daylight during winter to 14.5hrs during summer.

5.4 BARCELONA

This UC for Barcelona takes place on Premium line H12, which is an interurban fully straight bus route already in operation that crosses Barcelona and l'Hospitalet's cities diametrically, linking both localities. Route H12 is the Barcelona City eBRT demonstrator. It currently benefits from robust priority measures in the city center such as a double bus lane in the outward direction and a dedicated side lane in the opposite. Round trip length of the route is 22,56 km in length and 22 vehicles of Articulated/Biarticulated type service this route. The average bus frequency between 7.00 am to 9.00 pm is 7 min between buses. The average passenger boardings on a weekday was around 28,000 pax/day. Route H12 has a service regularity of 80% and a reliability of 4,133 km travelled before major maintenance is required on the bus.

The route consists of 34 stops each way, and the average speed ranges from 15.38km/h during the early mornings and late nights to 10.58km/h during peak hour. Thus, during peak hour traffic, it takes a little bit more than an hour (up to 65 minutes) for the bus to travel between two endpoints of the route. Throughout the operational time of 15h/day, each bus on average can make 6.5 return trips in Route H12; thus, with 350 operational days per year, each bus travels an annual distance of approximately 50.000 kilometers.

Route H12 is served by an 18m, 31-ton articulated bus with a capacity of approximately 150 passengers. The bus is powered by a 150kWh LTO battery and a 240kW electric motor system. The route has 2x 500kW opportunity chargers at both ends of the route to accommodate two buses charging simultaneously. The main concept of the Barcelona UC is the 50kW ~ 150kW modular chargers in the depot. Each modular charger can charge multiple buses simultaneously.

Barcelona has a warm Mediterranean climate, with hot summers and mild winters, where the temperatures range from 8 °C to 15 °C during winter and from 23 °C to 29 °C during summer. Barcelona experiences very light rainfall during summer and winter months, and heavier rainfall during spring and autumn, with a low of 25mm or rain over 3 days in December and a high of 90mm or rain over 6 days in October.

5.5 PRAGUE

The Prague UC is being deployed to route Linka 59, which is an airport bus line characterized as a high demand, high frequency suburban bus route connecting Prague Airport to the nearest metro station "Nádraží Veleslavín". Linka 59 is the result of the transformation of the high demand bus line no. 119, which connects Vaclav Havel Airport Prague to the nearest metro station "Nádraží Veleslavín", into an eBRT system. The diesel articulated vehicles are replaced by full electric operation by double-articulated battery trolleybuses using IMC technology. The IMC technology and eBRT concept is fully compatible with the "Clean Vehicle Directive", "Prague Climatic Commitment", and "Prague Climatic Plan". The direct result is that of local zero emission operation and reduction of noise level. There is an expectation of reducing the number of people who use private cars for traveling to Prague Airport. The key challenge of this demo is the efficient combination of in-motion charging section operation (trolleybus mode) and unwired section operation (battery mode) with possibility of opportunity charging at terminals and at the depot. The goal is to decrease the ratio of wired section to approx. 55-60% and to allow unwired connection between depot and bus line.

The running way is 18 km in length (both ways) with a 3-minute bus frequency during peak hours, operated by 17x 24m, 26-ton double articulated electric buses. The route is extremely heavy line with a total between 90,000 - 100,000 Timetable km/year/bus, with more transport capacity required. The planned passenger carrying capacity in Linka 59 is 20k passengers per day. The average speed of the line is 32.5km/h, and the total round-trip duration is 33 minutes. During the 20h operational time during the day, the buses make a total of 16 round trips, travelling 285kms days and 100k kilometers annually per bus. The buses are powered by an 82kWh LTO battery and 2x 180kW electric motors. The 2x 375kW IMC can supply a majority of the power requirement of the buses with the remaining being supplied from the battery. Since only 55% of the line falls in the IMC zone, approximately 9 buses out of the 17 are simultaneously connected to the IMC at any given time. This results in each bus consuming, on average, 83kW from the IMC.

Prague has a temperate oceanic climate with warm summers and chilly winters, with temperatures ranging from -1 °C to 3 °C during winter and from 16 °C to 26 °C during summer. There is rainfall throughout the year in Prague, but the highest rainfall occurs during summer with a precipitation of 67mm over 9 days, and the lowest occurs during winter with a precipitation of 19mm over 4 days. Daylight ranges from 8h during winter to 16.5h during summer.

5.6 RIMINI

In Rimini city, the targeted eBRT demo line, known as 'MetroMare', is across the Emilia-Romagna coastline. Rimini's eBRT line is the backbone of the future structure of sustainable mobility along Emilia-Romagna coastline. It connects the bus terminals between Rimini and Riccione railway stations in about 23 minutes with fully electric trolleybuses making 15 intermediate stops. The BRT line section has a length of 9.8km and is serviced with 18m full electric trolleybuses. The main driving force is transmitted through a 750V power line. These vehicles have three auxiliary battery packs with a total capacity of 45kWh which allow an operating range in autonomous running of about 12-15km. The service offered is approx. 600.000 km/year with a max capacity of 150 seats per trolleybus per ride:

giving the service a capacity of 1.2 million places per month during summer and 0.6 million places during winter season. The aim of the Rimini UC, in addition to the IMC system deployment, is real-time passenger counting onboard and at every stop, linked to the control center, to allow for a centralized trim service scheduling according to real service demand.

The line will be served by 4x 18m, 20-ton buses powered by 45kWh LTO battery and 2x 160kW electric motors. The IMC power is assumed to be 400kW and it is sufficient to provide the power requirements of the 4 buses simultaneously. The average speed of the line is approximately 26km/h, and it takes the buses an hour to make a round trip, including 7-minute wait times at either end of the route. The peak hour frequency of 15 minutes between buses. Each bus can make 20 round trips within the daily 20h operational time.

Rimini has a humid subtropical climate, moderated by the influence of the Adriatic Sea, with cool winters and hot summers. The temperature ranges from 0 °C to 8 °C during winter and from 18 °C to 29 °C during summer. There is rainfall throughout the year, with the highest during summer with 73mm of rainfall over 4 days, and the lowest during winter with 29mm of rainfall over 4 days. Rimini has 9h of daylight during winter going up to 15.5h of daylight during summer.

6 USE CASES RESULTS AND ANALYSIS

In this chapter, the results using the EBRT simulation tool and its functionalities described in D3.1 are presented for the different use cases, in function of their eco-strategies, at fleet level, also considering the baseline eBRT line in Nantes. The results have been discussed with the different use case leaders in eBRT2030 project, with several iterations to improve the accuracy of the results. Further discussions will take place as the demonstrations are progressing with real measurements. In this chapter the results are also analyzed to assess the simulation framework and its ability to closely replicate the behavior of a large variety of scenarios and technologies on eBRT lines. Finally, this is extended to the eBRT concept for all, which will be further considered in WP9.

6.1 BASELINE EBRT RESULTS

The baseline scenario is taken from Nantes, France, where is there is an already established e-BRT line. The measurement data from the 24m double articulated e-buses indicate an average energy usage of 1.96 kWh/km. The breakdown in the power consumption of the buses are as follows: 143.1kW by the electric motors, 13.6kW by the auxiliary systems, 25.5kW due to heating, 4.8kW from the resistor, and 3.6kW by the brakes. The opportunity charging via the pantograph had a power of 561kW on average. Figure 7 and Figure 8 show the power consumption and the SoC of the battery, respectively. The energy requirements for the baseline eBRT in Nantes show significantly less energy needed for the 24m double articulated buses when compared to a similar class of buses in Prague; in fact, the energy requirement for the 24m bus in Nantes is more comparable to the 18m buses used in the cities of Athens, Barcelona, and Rimini. A reason for this disparity can be explained due to the low power (150kW) traction system used in the buses in Nantes compared to higher powered (250kW ~ 350kW) systems used in the Use Case cities. Another reason could be the milder climate in Nantes compared to the Use Case cities, which are either colder (Amsterdam, Prague, Rimini) or hotter (Athens, Barcelona); thus, the auxiliary energy requirements are much lower in Nantes than in the other cities. A final reason could be the charging strategy used in Nantes, which has 12 opportunity chargers located throughout the route, so the high-capacities battery is frequently kept in a higher SoC band (>60%) throughout the operational time, while the routes in the Use Case cities, either have chargers located only in the ends of the route or are trolleybus having very small capacity batteries. Since the energy requirements in Nantes are lower, the energy saving strategies are not considered.

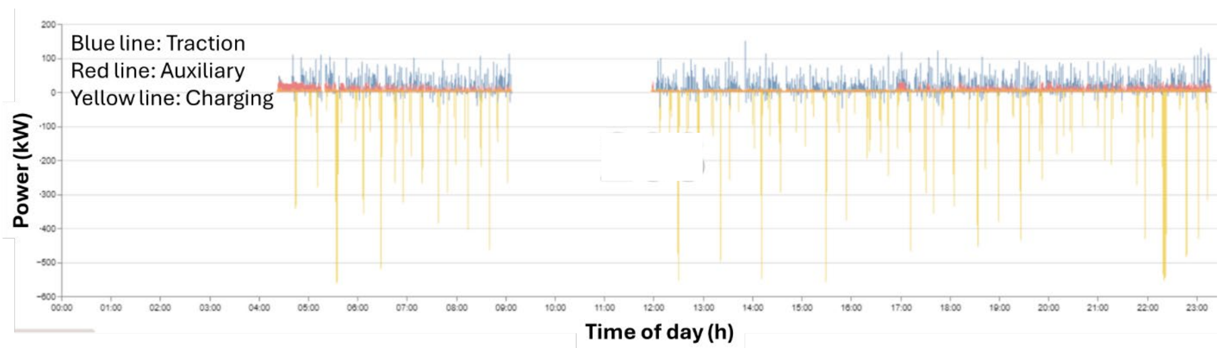

Figure 7. Baseline power utilization in 18m buses in Nantes, France.

Figure 8. Baseline SoC profile for 18m bus in Nantes, France.

6.2 FLEET RESULTS FOR CITIES WITHOUT ENERGY SAVING STRATEGIES

This section provides simulation results for the participating cities for the different seasons. The data will start with a comparison of the average energy utilization (in kWh/km) of the buses, the average fleet TCO (in €/km), and the total daily electricity consumption by the fleet in the different cities and for different seasons. The data also considers the split in the energy between the traction and the different auxiliary systems.

6.2.1 AMSTERDAM

The results are shown in Table 5 for Amsterdam with 18m buses, 32 bus fleet, 33 km/h to 38 km/h route speed and an average of 388 km daily travel.

Table 5. Baseline Energy Requirements in Amsterdam UC scenario.

Season	Electricity Consumption (kVAh)	Fleet Energy Utilization (kWh/km/bus)	TCO (€/km/bus)	Traction Energy (kWh)	Auxiliary Energy (kWh)
Spring	18766	1.235	0.7545	640.7	055.92
Summer	19032	1.254	0.7552	639.0	068.52
Autumn	18645	1.226	0.7541	643.4	048.63
Winter	21351	1.407	0.7614	648.2	145.40

NOTE: The electricity consumption during winter was 13.5% higher than the other seasons.

6.2.2 ATHENS

The results are shown in Table 6 for Athens with 18m buses, 2 bus fleet, 15.5km/h to 21 km/h route speed and 275 km of daily travel.

Table 6. Baseline Energy Requirements in Athens UC scenario.

Season	Electricity Consumption (kVAh)	Fleet Energy Utilization (kWh/km/bus)	TCO (€/km/bus)	Traction Energy (kWh)	Auxiliary Energy (kWh)
Spring	1354.2	1.9996	0.9283	369.10	179.58

Summer	1551.3	2.2988	0.9355	369.19	261.59
Autumn	1393.2	2.0588	0.9297	369.18	195.74
Winter	1372.3	2.0256	0.9290	369.84	185.97

NOTE: The electricity consumption during summer was 13% higher than the other seasons.

6.2.3 BARCELONA

The results are shown in Table 7 for Barcelona with 18m buses, 22 bus fleet, 10.5km/h to 15.5km/h route speed and 158 km of daily travel.

Table 7. Baseline Energy Requirements in Barcelona UC scenario.

Season	Electricity Consumption (kVAh)	Fleet Energy Utilization (kWh/km/bus)	TCO (€/km/bus)	Traction Energy (kWh)	Auxiliary Energy (kWh)
Spring	11684	2.3053	1.2144	212.33	151.73
Summer	14156	2.7111	1.2252	212.33	215.80
Autumn	12494	2.4537	1.2184	212.33	175.16
Winter	10591	2.0950	1.2094	212.32	118.52

NOTE: The electricity consumption during summer was 33% higher than in winter.

6.2.4 PRAGUE

The results are shown in Table 8 for Prague with 24m buses, 17 bus fleet, 32.5km/h average route speed and 280 km of daily travel.

Table 8. Baseline Energy Requirements in Prague UC scenario.

Season	Electricity Consumption (kVAh)	Fleet Energy Utilization (kWh/km/bus)	TCO (€/km/bus)	Traction Energy (kWh)	Auxiliary Energy (kWh)
Spring	20320	3.3255	1.0173	723.82	209.97
Summer	21193	3.5305	1.0216	719.72	271.69
Autumn	19868	3.2369	1.0160	722.96	185.95
Winter	19642	3.1700	1.0154	725.28	164.84

NOTE: The electricity consumption during summer was 13% higher than in autumn and winter.

6.2.5 RIMINI

The results are shown in Table 9 for Rimini with 18m buses, 4 bus fleet, 26km/h average route speed, 400km daily travel.

Table 9. Baseline Energy Requirements in Rimini UC scenario.

Season	Electricity Consumption (kVAh)	Fleet Energy Utilization (kWh/km/bus)	TCO (€/km/bus)	Traction Energy (kWh)	Auxiliary Energy (kWh)
Spring	3332.8	1.6754	0.6655	491.06	179.09
Summer	3638.8	1.8353	0.6705	489.93	244.20
Autumn	3316.1	1.6678	0.6655	491.14	175.99
Winter	3747.9	1.8884	0.6717	492.11	263.23

NOTE: The electricity consumption during winter was 13% higher than in spring and autumn.

6.2.6 SUMMARY DISCUSSION

The energy required for traction remained consistent regardless of the season since the driving cycle, elevation profile, and passenger profile remained the same. Moreover, the baseline driving style is based on the number of bus stops, the average speed of the route, and the maximum acceleration and deceleration of the vehicle; this information was provided by the PTA partners during the data collection stage in T3.1. This information is combined with the travel time between bus stops that is extracted from the bus schedule provided on the PTA website to estimate the distance between the stops. With this information in hand, a trapezoidal velocity profile is calculated, such that the vehicle will accelerate using its maximum acceleration to a given speed, then travel at this speed for a set time and then decelerate using its maximum deceleration to a standstill; the total time taken should be the travel time between bus stops, the total distance traveled using this method (i.e., the area under the trapezoidal velocity profile) should be the distance between the bus stops, and the average speed of the trapezoidal velocity profile should match the average speed of the route. The baseline assumes that the bus travels in a BRT corridor, or the bus has right of way, such that the bus can travel at a constant speed in between bus stops. An example of this baseline driving strategy is shown in Figure 9. On the other hand, the energy required for auxiliary varied with the seasons indicating different cooling and heating requirements during different weather conditions. For hot climates, the energy required during summer far exceeded that in winter, while for temperate climates, the energy required for winter was higher.

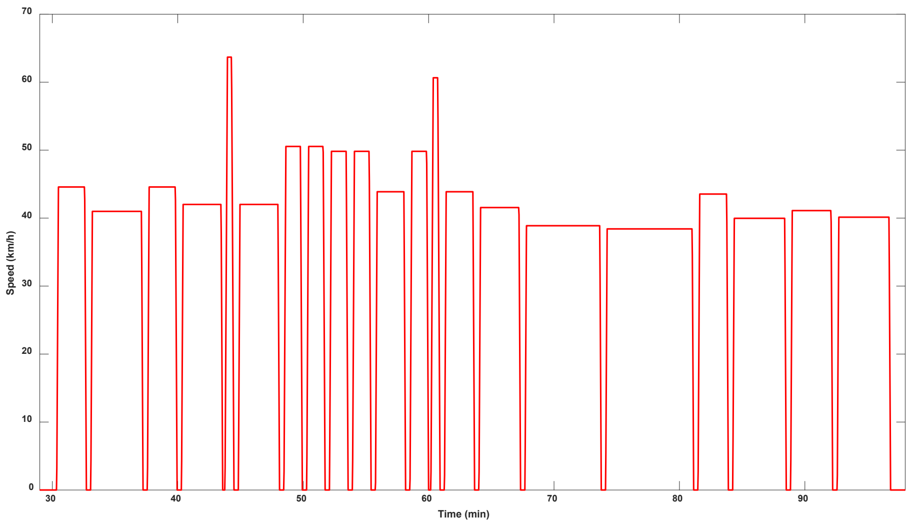

Figure 9. An example of a baseline driving strategy.

6.3 FLEET RESULTS FOR CITIES WITH ENERGY SAVING VIA ECO-STRATEGIES

This section provides the simulation results when a specific ECO-feature is activated. Mainly two ECO-features are considered, namely ECO-comfort and ECO-driving. ECO-comfort affects the auxiliary system, so the results for ECO-comfort show the reduction of the vehicle's energy requirements as well as the auxiliary system's energy requirements. Furthermore, ECO-comfort is analyzed for both summertime and wintertime operation to differentiate the effectiveness of the algorithm with widely different climate conditions. On the other hand, ECO-driving affects the traction system, so the results for ECO-comfort show the reduction of the vehicle's energy requirements as well as the traction system's energy requirements, as well as how much energy can be recovered during regenerative braking due to the modification of the driving style. Finally, ECO-charging was not considered in this report since the opportunity charging duration given was too low to reduce charging c-rate by applying pulsed charging. All applications of ECO-charging resulted in the battery completely discharging at some points during the daily operational schedule.

6.3.1 ECO-COMFORT (SUMMER)

The results considering the ECO-comfort strategy and its possible energy reduction in the different cities during summer are shown in Table 10.

Table 10. Possible energy reduction due to ECO-comfort in different cities during summer.

City	Fleet Energy Utilization (kWh/km/bus)	Reduction (%)	Auxiliary Energy (kWh)	Reduction (%)
Amsterdam	1.2250	2.31%	052.40	23.53%
Athens	2.0916	9.01%	204.69	21.75%
Barcelona	2.5539	5.80%	190.98	11.5%
Prague	3.5264	No reduction	273.53	No reduction
Rimini	1.6557	9.79%	172.35	29.42%

6.3.2 ECO-COMFORT (WINTER)

The results considering the ECO-comfort strategy and its possible energy reduction in the different cities during winter are shown in Table 11.

Table 11. Possible energy reduction due to ECO-comfort in different cities during winter.

City	Fleet Energy Utilization (kWh/km/bus)	Reduction (%)	Auxiliary Energy (kWh)	Reduction (%)
Amsterdam	1.3270	05.69%	100.30	31.04%
Athens	1.8574	08.30%	139.80	24.83%
Barcelona	2.0799	No reduction	116.13	No reduction
Prague	3.5169	No reduction	285.71	No reduction
Rimini	1.6749	11.31%	177.84	32.44%

6.3.3 ECO-DRIVING

The results considering the ECO-driving strategy and its possible energy reduction in the different cities during summer are shown in Table 12.

Table 12. Possible energy reduction due to ECO-driving in different cities.

City	Fleet Energy Utilization (kWh/km/bus)	Reduction (%)	Traction Energy (kWh)	Reduction (%)	Braking Recovery (%)	ECO-Brake Recovery (%)
Amsterdam	1.2300	12.58%	550.70	15.02%	71.70%	92.00%
Athens	1.8570	19.22%	247.92	32.85%	76.17%	93.32%
Barcelona	2.6216	03.30%	198.20	06.65%	61.40%	62.25%
Prague	2.7309	22.65%	496.18	31.09%	85.63%	93.07%
Rimini	1.5738	14.25%	391.52	20.09%	73.34%	89.13%

6.3.4 SUMMARY DISCUSSION

ECO-comfort reduces the auxiliary energy consumption, while ECO-driving reduces the traction energy consumption. Auxiliary energy consumption is a smaller percentage of the total energy consumption of the vehicle compared to traction energy consumption. For ECO-comfort the reduction in the auxiliary energy consumption depends a lot on the initial climate control strategy implemented in the vehicle by the PTA; since the initial climate control strategy for the different cities were differently applied by the various PTAs, the reduction in the energy requirements due to ECO-comfort are not comparable across cities or climate as shown in Figure 10.

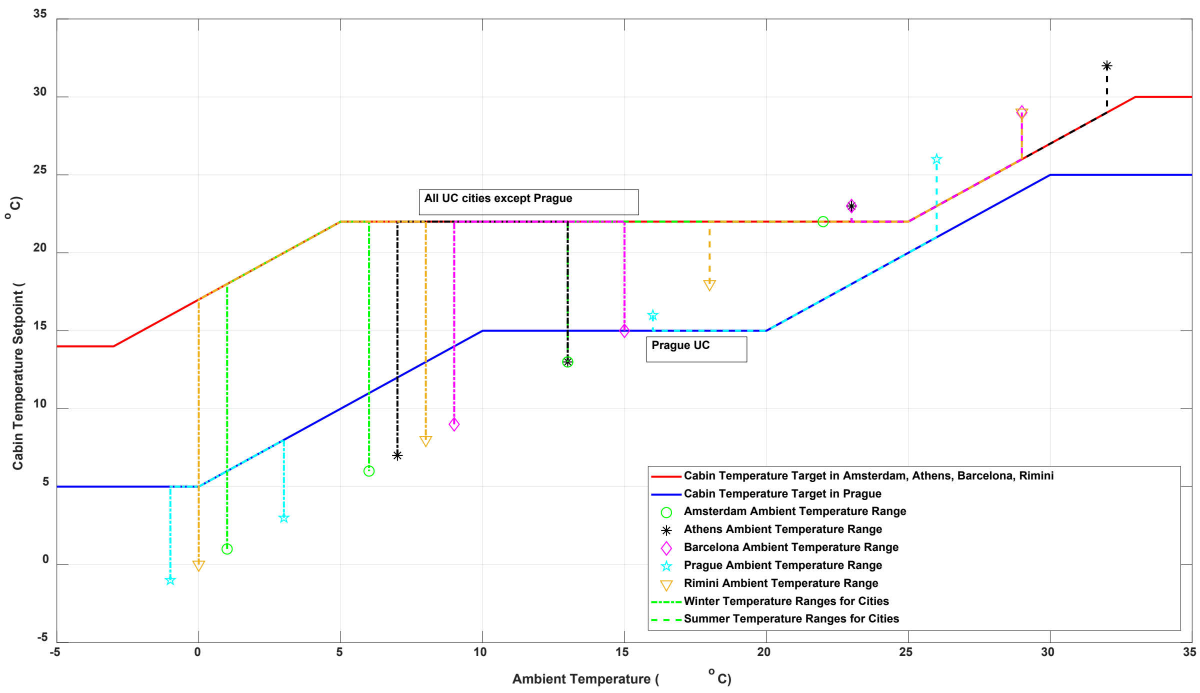

Figure 10. Temperature profile vs cabin setpoint temperature for UC cities

The energy required by the auxiliary system for climate control depends on a variety of factors; namely, the difference between the ambient temperature and the cabin setpoint temperature, the availability of recovering and utilizing waste heat for heating operation, and the coefficient of performance (COP) of the heat pump during heating or cooling operation. Figure 10 illustrates why some cities may have a higher auxiliary power requirement during winter for heating operation compared to other cities. From the figure it can be concluded that Athens will have a higher energy requirement for heating than Barcelona, and a lower energy requirement than Rimini. This is because the difference between the cabin setpoint temperature and the ambient temperature is higher for Athens than for Barcelona, but compared to Rimini, the difference is lesser. Contrasting with the heating requirements, the figure shows that the cooling requirements for the three cities would be similar (with some variation) because the difference between the ambient temperature and the cabin setpoint temperature for cooling is almost similar for the three cities.

A second factor in energy consumption relates to the availability of utilizing the waste heat generated for heating purposes, but a similar option is not present for cooling. Many components in the vehicle powertrain generate waste heat, including the power electronics, the battery, the electric motor, and the friction brakes; thus, an excess amount of heat is available for heating purposes when the vehicle is in operation. This is why simulation results show that the heat pump requires lesser energy for heating purposes than for cooling purposes for many cities, unless the difference between the ambient and the setpoint temperature is excessive, like in the case of Rimini during winter.

For Prague UC, the PTA has provided different cabin setpoint temperature range, which is on average 7°C lower than the cabin setpoint temperature range for the other UC cities, as shown in Figure 10. The lower cabin setpoint temperature for Prague UC makes it more balanced compared to the ambient temperature in Prague, since the difference between the ambient and the setpoint temperature, during winter, is very low compared to the other UCs. This avoids the excessive heating energy requirements for Prague, unlike in Rimini. Combining this factor with the ability to use waste heat to aid in heating the cabin results in a lot less auxiliary energy requirements during winter compared to summer. This makes the PTA defined cabin setpoint temperature an optimal temperature, for HVAC operation, when compared to the winter and summer ambient temperatures. This is why in Prague, ECO-comfort did not offer any reduction in the auxiliary energy consumption, since the climate control strategy used in Prague UC already provided the optimal cabin reference temperature during summer as well as winter.

The reasons provided above explains why, in Barcelona, the auxiliary system consumed twice as much energy to keep the cabin cool during summer than it consumed to keep the cabin heated during winter. Thus, applying the ECO-comfort algorithm decreased the energy consumption of the auxiliary system by a significant amount in summer, whereas in winter, when the energy consumption was already low, there was no reduction in energy consumption. It is also why, although the same climate control strategy used in Barcelona was also used in Athens, there was higher auxiliary energy consumption during both summer and in winter in Athens; thus, ECO-comfort offered lots of energy savings in both summer and winter in Athens. In conclusion, ECO-comfort offers energy savings, only when the cabin reference temperature achieved due to climate control strategy is non-optimal for that temperature. However, if the reference temperature due to climate control strategy is already at the optimal level for that temperature, ECO-comfort provides minimal or no savings.

The reduction in the traction energy is the same using ECO-driving regardless of the season, and part of the reduction comes from the improved energy recovery during regenerative braking, and the other part comes from the improved vehicle kinematics (i.e., changes in speed and acceleration). A final point to note for ECO-driving is the fact that it is less effective for lower average speeds, therefore in Barcelona, where the speed in the route ranges from 10km/h to 15km/h, there is not much reduction in energy requirements, nor is there effective energy recovery during regenerative braking. Whereas in Prague, where the average speed is 32.5km/h, there is the highest energy recovery from regenerative braking. It should be noted that the simulation does not consider traffic situations like slowing down at intersections or during turns, traffic density, and stopping at traffic lights, because it is not based on actual GPS coordinates. However, if distance-based constraints are provided as input data (e.g., bus must stop at this location due to red light, cannot go over this speed limit in these regions etc.), the simulation platform (as well as the ECO-driving algorithm) can be adapted to honor those constraints.

6.4 ANALYSIS OF RESULTS AND COMPARISON TO BASELINE

To simulate operation under various conditions from different use cases, the battery specifications, including the battery chemistry, capacity, operational SoC range, and maximum currents are considered in the simulation as provided by project partners, and so are chargers specifications, such as opportunity chargers, charging in the depot, or IMC.

Vehicle electric motors and gearbox parameters, such as rated power, maximum torque and rated motor speed are also considered, either based on partner's data or on assumptions based on known technologies. Parameters are set, based on available online information such as operators' timetables, and data provided by partners. Complementary assumptions are made and checked with local partners regarding operations as detailed in Table 13.

HVAC modeled systems account for real behavior: energy consumption levels during summer are higher than in winter for warmer climate such as Barcelona (+29% for Barcelona, +17% for Athens), and higher during winter than in summer for more continental climates such as Prague. For the latter, real data shows an increase of +19% in total energy consumption per km during winter season. Indeed, energy consumed by HVAC increases by 140% with an average temperature dropping from 7.4°C to 0.3°C. For lowest temperatures, extra energy consumed for heating can even result in shortened rides when battery capacity cannot cover the energy demand. This is close to model estimation showing a difference of +26% energy consumption between January and April, and +22% when comparing January to the average of other seasons.

Speed profiles throughout the day are deemed realistic from an operating perspective. Average speed values stand between 10 and 35km/h. Minor deviations can occur when buses do not stop at every station, depending on passengers' origin and destination. This can account for higher speeds, and lower energy consumption for a few buses but can be neglected at the fleet scale. Indeed, stop time assumption at each bus stop is constant – 10 to 30 seconds – regardless of the number of passengers alighting and onboarding. When fast charging is implemented at a station, this average does not reflect real charging time that can be longer at major hubs (e.g. lots of passengers boarding and alighting, taking more than 20 seconds) or shorter for smaller stations. However, this approximation has no impact on overall consumption profiles, for all charging strategies.

Regarding speed and ECO driving, features are well defined and show good results but require some flexibility in the bus schedules. Driving with eco mode involves smoother acceleration/deceleration phases and has an impact on timetables, drivers, and so weighs on operational costs. The first field of application is off-peak hours, where higher commercial speed is less of a priority.

Table 13. Example of scenario requirements and assumptions for the European Use Case cities.

Parameter	Amsterdam	Athens	Barcelona	Prague	Rimini
Route name	Line 300	Line B10	H12	Linka 59	Metro Mare
Route length (both ways)	80.6 km	9.8 km	22.56 km	17.55 km	20 km
Total stops (both ways)	42	30	68	19	32
Route speed	33 km/h to 38 km/h	15.5 km/h to 21 km/h	10.5 km/h to 15.4 km/h	27.7 km/h to 30.1 km/h	26.1 km/h
Charging type	All charging at depot; include high and medium power chargers	Overnight charging at depot; opportunity charging at one end of the route	Overnight charging at depots; opportunity charging at both ends of the route; depot charger is modular	IMC charging for 55% of the route, opportunity charging at the airport, overnight charging at depot	IMC charging for the entire route
Charger power	High power: 300 kW Medium power: 150kW	Opportunity: 350 kW Depot: 120 kW	Opportunity: 500 kW Depot: 150 kW	Opportunity: 75 kW Depot: 45 kW IMC: 375 kW	IMC: 225 kW

Number of chargers	High power: 17 Medium power: 25	Opportunity: 1 Depot: 1	Opportunity: 4 Depot: 22	Opportunity: 1 Depot: 21 IMC: 2	IMC: 1
Number of trips	4.5 to 7 return trips/day/bus	28 return trips/day/bus	7 return trips/day/bus	16 return trips/day/bus	20 return trips/day/bus
Total trip duration	77 minutes / return trip (including 2 minutes layover time at both ends)	43.5 minutes / return trip (including 2.75 minutes of lay over at both ends)	143 minutes / return trip (including layover time of 7 minutes & 4 minutes of charging at both ends)	76.5 minutes / return trip (including layover time of 20 minutes at both ends, charging time included)	60 minutes / return trip (including layover time of 7 minutes at both ends)
Bus Frequency	7.5 minutes	20 minutes	6.5 minutes	4.5 minutes	15 minutes
Stop times	20 seconds at each stop	15 seconds at each stop, 30 during peak	15 to 20 seconds stop at each stop	10 to 20 seconds stop at each stop	20 seconds at each stop
Number of buses	32	2	22	17 (+3 spare)	4 (+5 spare)
Bus type	18m bus	18m bus	18m bus	24m trolleybus	18m trolleybus
Passenger max	150	145	150	180	130
Battery size	527.4kWh LTO	520 kWh NMC	147.5kWh LTO	81.9 kWh LTO	46.4 kWh LTO
Motor size	2 x 125 kW	375 kW	235 kW	2 x 195 kW	2 x 160 kW

When available, passenger load within the bus is also considered. They have an impact on total weight and thus on energy consumption. An increase of 25% in passengers is estimated to cause an increase of 20% in energy consumption. Therefore, mis-predicting peaks in ridership can have significant impact on one bus consumption and impact the charging strategy if facilities are designed without any safety margin. However, peaks can be fine-tuned and adapted based on surveys data as shown in Figure 11. Only disruptions could cause such a deviation.

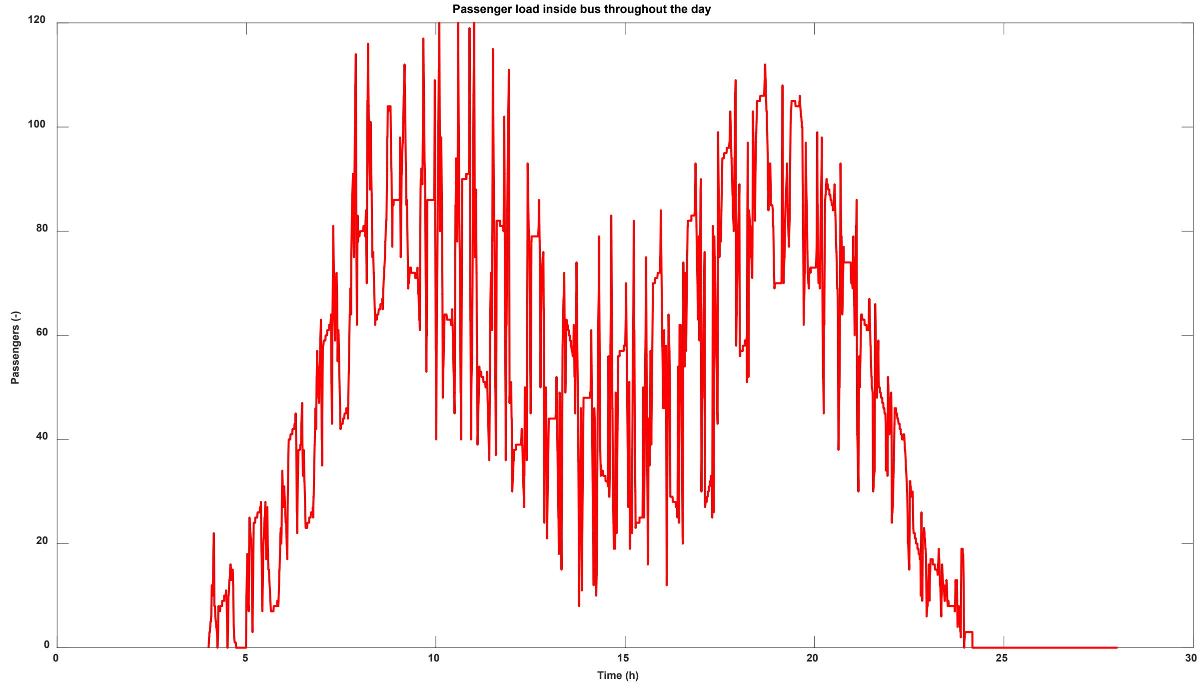

Figure 11. Example of passenger model for Prague Use Case.

As for charging strategies for modular charging, each charger is used equally during the day in the simulation. This is ideal as it flattens the usage, reduces maintenance costs and increases the lifespan of infrastructure. However, this is rarely the case, due to chargers being affected to buses and buses consumption showing discrepancies due to various ridership levels. On the long term, this deviation between model and reality should not be significant as operations tend to balance the chargers use from one day to another. This problem can also occur for opportunity charging. As an example, Barcelona implemented extra chargers not to face queueing at terminals, when charging time was longer than expected.

In the model, the same interval between buses is used throughout the day. Practically, this interval matches ridership levels. The higher the demand, the smaller the interval. Simulation rightfully considers minimum interval, reflecting worst case scenario to validate infrastructure capacity. Yet, this overestimates total kilometers made, and so, total energy consumed. Yet, the model can be fine-tuned if different peak hour/off-peak hour intervals are specified or if the bus schedule from a bus's point of view is supplied for consideration.

Summary discussion

Deviations between model and reality can be linked to inputs in operational data and electrical and environmental characteristics. However, the model can be fine-tuned and segmented so that daily operations are simulated differently depending on peak hour and off-peak hour operations. The model will be calibrated at a further stage of the eBRT2030 project using UC demo datasets.

6.5 DEFINITION OF REFERENCE EBRT SYSTEM FOR EBRT CONCEPT FOR ALL

The EBRT concept for all will be developed in WP9 stepping on the initially developed EBRT reference concept in T2.1 which will be updated with learnings from operational perspective from the project pilots. This step includes also embedding insights from the multi-level design and simulation tool developed in T3.1. The aim is to capture a variety of operational conditions and cases that cannot be fully covered and explored in real operational environments of the pilot locations, through a cross-reference simulation study that can help identify various boundaries for EBRT deployments. An emphasis will be put in studying the impact of major operational factors as:

- Deployment of charging infra and charging scenarios organization
- Utilizing different vehicle technologies
- Implication on the batteries and their capacity
- Vehicle load of passengers
- Operating environment and climate conditions
- Yearly variation of the passenger load and climate conditions
- Energy needs – needed grid connection/ grid impact, energy to power the whole fleet

Therefore, an evaluation of the eBRT operational scenario performance of the demo cities will be conducted with the help of the simulation tool, e.g. replicating the Barcelona scenario to Athens, etc. In addition, the same scenarios will be tested in other cities (follower cities/other cities in EU) to evaluate boundary conditions for deployment.

7 CONCLUSION

The report focuses on the simulation results of the UC scenarios in the different European cities to understand the energy requirements of the bus fleet as well as the charging requirements. The simulations also provide an understanding of the grid capacity required to meet the dynamic charging demands. The simulation framework that underpins the simulations has been improved from the baseline framework taken from ASSURED. This report builds upon the new functionalities included in the simulation platform and detailed in D3.1, including IMC, modular charging, battery backup, dynamic speed and passenger model, and bidirectional charging are some of the improvements that have been implemented in the eBRT2030 simulation framework.

The different eco-strategies (eco-comfort, eco-charging, eco-driving) are described and applied to the different use cases. In particular, the use cases of Amsterdam (NL), Athens (GR), Barcelona (ES), Prague (CZ) and Rimini (IT) are described together with a reference use case in Nantes, France.

The above-mentioned tools, strategies and use cases are used to provide the simulation results under different operating conditions. The simulation results indicate that ECO-comfort and ECO-driving are very effective in reducing the energy requirement of the vehicles and thus improving driving range; however, they each have their constraints. Simulation results show that normal mode driving for 24m buses require between 2 kWh/km to 3.5 kWh/km of energy usage, while the 18m buses require between 1.2 kWh/km to 2.7 kWh/km of energy. That makes, on average, a 24m bus requires 40% more energy than an 18m bus. The wide variation in energy usage is a result of the different climate and driving conditions in the UC cities. ECO-comfort reduces the auxiliary energy consumption, but that reduction is dependent on the initial cabin climate control strategy and is dependent on the season when it is implemented. It was seen from simulation results that the higher the normal mode auxiliary energy usage, the greater the effects of ECO-comfort. ECO-driving does not depend on the season, but on the average speed of the vehicle on the road, with higher average route speed resulting in more energy savings due to more effective regenerative braking. Simulation results show that the application of ECO-comfort reduces up to 11% of the overall vehicle energy consumption, while ECO-driving was able to reduce up to 22% in energy usage. ECO-charging was not applicable in these simulations, since the battery temperature did not exceed the provided threshold temperature for ECO-charging to activate, and in some of the UC scenarios, there was not sufficient remaining SoC to implement reduced-power charging strategy.

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