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Electric Buses: Challenges of Operating an e-Bus in Mexico City

Case Study: Metrobus Line 3

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1. Introduction and Objectives

Global warming and climate change are strong motivators for creating a more sustainable world. In the area of transportation, minimizing emissions and moving towards electric transportation are a universal and irreversible trend of the time. The transition to electric vehicles (EVs) presents one of the most significant operational challenges for mobility-driven companies. The shift to this new technology entails a wide range of complex problems, particularly in large-scale, high-demand environments. When it comes to designing a fully electric passenger bus operation, the challenge is even greater. Factors such as limited average speeds, limited battery energy, frequent stop-and-go conditions, variable passenger loads throughout the day, climate control demands, external environmental conditions, and diverse driving patterns all play a critical role in shaping operational performance.

In this context, Mexico City offers a particularly demanding testbed. Its mix of topographic variability, high urban density, and a large floating population makes it a prime environment to evaluate and improve electric bus performance. Specific challenges include:

a) High Traffic Congestion

High stop-and-go frequency increases energy demand and wear on regenerative systems.

b) Shifting and Dispersed Demand

The city's large floating population and variable demand across districts and times of day require route flexibility and, in some cases, demand-responsive service models.

c) Integration with Existing Transport Systems

Mexico City's multimodal network—comprising Metro, RTP, trolleybuses, minibuses, and taxis—demands that new electric routes ensure seamless connectivity while avoiding redundancy and overcrowding at major hubs.

d) Budget and Financing

Launching a new route demands significant investment in electric fleets, infrastructure, and operational planning. Inherently, proposals must be grounded in detailed cost-benefit analyses and accurate demand forecasting.

Despite these challenges, electric buses offer a viable and sustainable solution for urban mobility—provided that operational strategies and simulations are robust enough to reflect real-world conditions.

This whitepaper explores simulation-based strategies and route-level variables tailored to the urban and environmental context of Mexico City, with the goal of designing effective, fully electric bus operations. Special attention is given to energy-saving strategies applicable in dedicated lane, stop-to-stop operations. Leveraging prior studies on optimal speed trajectories, we show that energy savings of 25–40% are achievable in low-

speed corridors without mixed traffic.

To that end, this whitepaper aims to:

- Characterize the operational, environmental, and energy-related variables influencing electric vehicles performance.
- Analyze telemetry and route-specific data for Metrobus Line 3.
- Simulate realistic operating conditions and charging cycles.
- Quantify the benefits of optimization strategies such as eco-driving, regenerative braking, and AC load management.

1.1. Metrobus Line 3 Electrification Context

Route snapshot

Metrobus Line 3 is a 20 km bus-rapid-transit (BRT) corridor running north-south from Tenayuca to Pueblo Santa Cruz Atoyac, serving 36 stations along the Insurgentes axis. The line moves $\approx 200,000$ passengers per day, making it one of the busiest BRT corridors in Mexico City. [1]

Fleet conversion

In February 2023 the route became Latin America's first 100 % electric articulated BRT line after the deployment of 60 Yutong E18 buses (18 m, 160-passenger capacity). Each bus carries a lithium-ferrophosphate (LFP) battery of ≈ 563 kWh, providing an autonomy of ≈ 330 km (≈ 8 round trips) on a single overnight charge (VEMO monitors only 10 out of the 60 buses that cover Metrobus Line 3 operation as a whole). [2]

Charging ecosystem & investment

Charging is centralized at the Júpiter depot, fitted with 32 DC fast chargers (180 kW each, ≈ 5 MW aggregate) that replenish a bus in ≈ 5 h. The fleet renewal and infrastructure required a MXN 900 million ($\approx$ USD 49 million) private investment led by Mobility ADO (MIVSA) and financed by Santander México. [3]

Environmental impact

Full electrification avoids an estimated 7,500 t CO₂ per year, equivalent to planting $\approx 45\,000$ mature trees, while eliminating local PM and NO_x tail-pipe emissions along the corridor.[4]

Operational performance (2024 telemetry)

- Average in-service energy use: 1 kWh per km, 20 % below the diesel baseline. (internal VEMO Dataset).
- Average daily distance per bus: 247 km.

These benchmarks are the basis for lifecycle cost and battery-degradation projections in later sections (internal VEMO dataset).

2. Operational Characterization

A successful transition to electric bus operations in complex urban environments requires a thorough understanding of real-world operational conditions. Key variables and available data are fundamental for accurate simulation and strategic planning. These include telemetry data, route characteristics, environmental conditions, and battery-related performance factors.

2.1 Real World and Simulated Vehicle/Route Data

A robust dataset derived from vehicle telemetry is essential for modeling the energy consumption and operational behavior of electric buses. The available telemetry includes:

- **Velocity profiles:** Real-time vehicle speed across various operating conditions (traffic, stops, etc.).

Velocity Profile

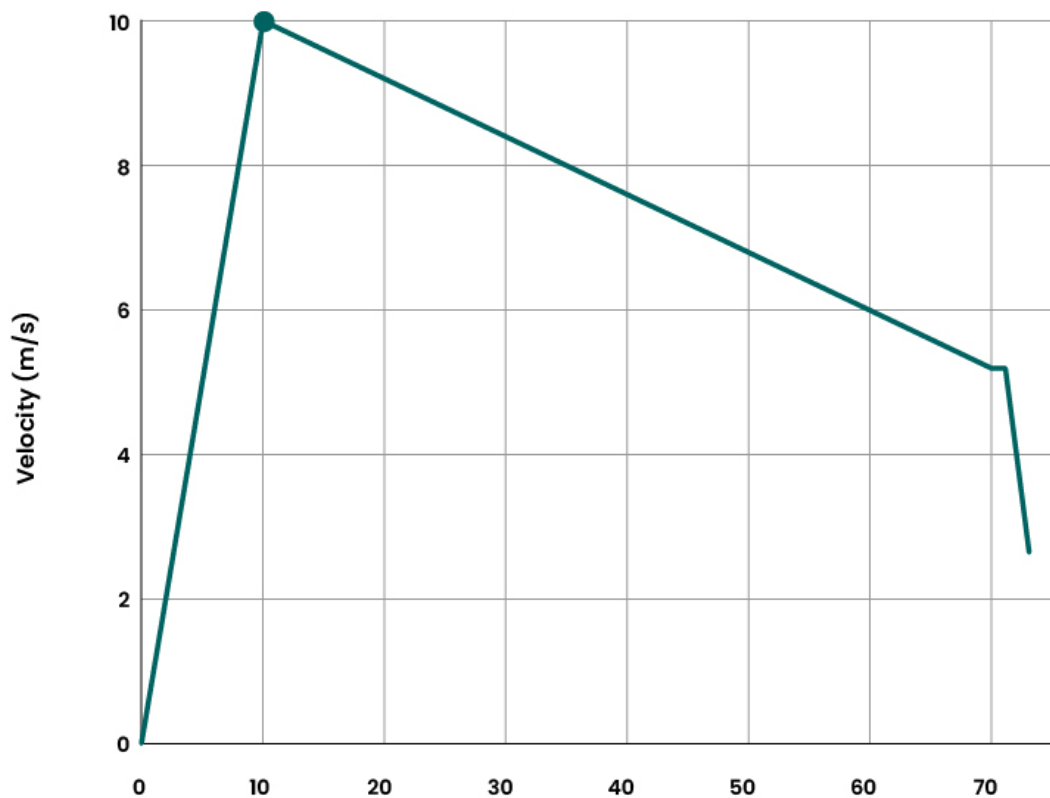


Figure 1 – Optimal Velocity Profile shown as speed in m/s over time in seconds

Stop-to-Stop velocity profiles can significantly vary due to distance, required average speed, vehicle, cross traffic and several other factors.

Velocity profiles show the variability of speed over time. In this case, x-axis shows time in seconds. An energy-optimal velocity profile is shown in Figure 1 and entails a distinct acceleration phase (0–10s), followed by a cruising segment and finally deceleration. (The Figure shows a simulated speed trajectory over 500m).

- Drive cycles:** Acceleration, idling, regenerative braking, and coasting patterns were extracted to define realistic driving loops. Profiles match Mexico City Line 3 schedules and peak hour conditions. Typical trip includes 38 stop/start events in a 20 km segment, averaging a peak deceleration of -1m/s^2 . The average segment length therefore is approximately 566 meters, with a maximum speed of approximately 40 km/h.
- Energy consumption rates:** Power demand data disaggregated by time, location, and operational state.

Battery energy Over Time

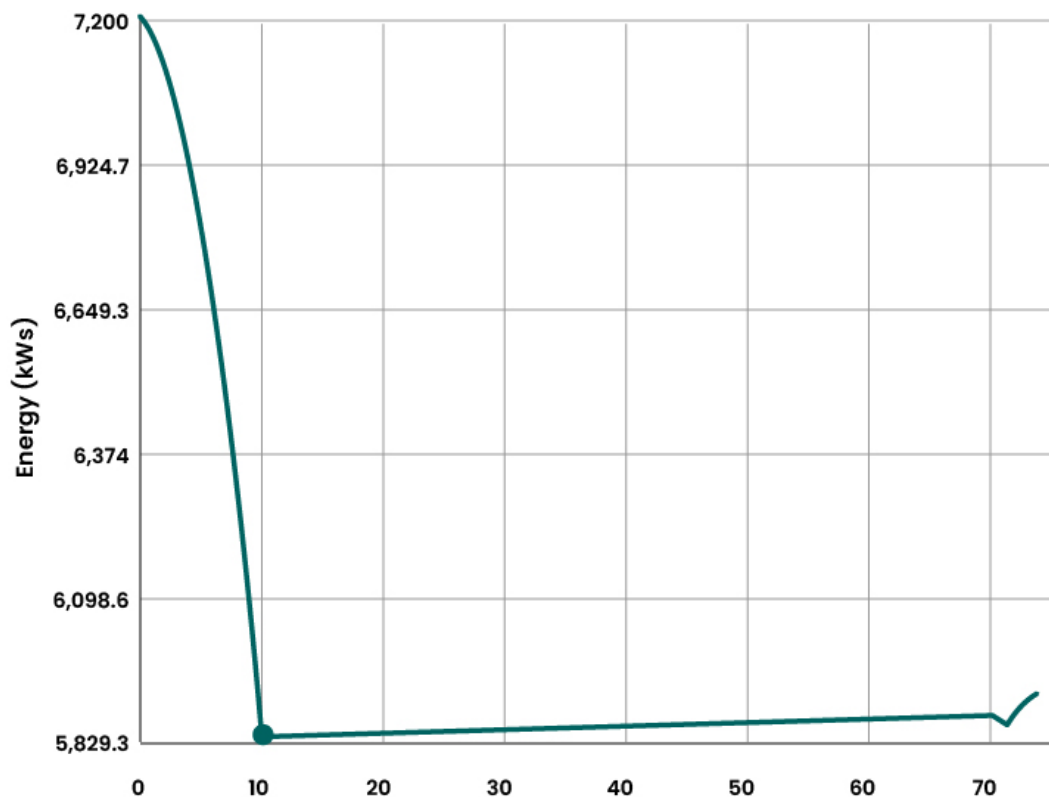


Figure 2 – Remaining Battery energy as a function of time for the velocity profile in Figure 1.

The energy profile shows battery energy during a stop-to-stop segment. In this case, speed increases during the first few seconds, and remaining battery energy decreases at a higher rate, starting at 2 kWh. After 10 seconds of accelerating, the battery keeps on delivering energy but

at a much lower and more constant rate. During deceleration, a slight increase in battery energy is seen due to regenerative braking until the bus comes to a complete stop.

- **Auxiliary loads:** Energy used by onboard systems, including air conditioning and heating. Based on real operational data, no energy was consumed by HVAC or auxiliary heating systems during operation.

2.2 Route Distance and Elevation Profiles

Route geometry plays a key role in determining energy consumption and regenerative braking efficiency. The operational network under study includes:

- **Route lengths:** Segments analyzed include stop-to-stop distances between 500 m and 1,000 m.
- **Elevation changes:** Some routes present significant elevation differences, with inclines exceeding 4% in hilly districts such as Coyoacán and Álvaro Obregón. These topographical elements impact motor load and battery performance. In the simulations shown here, we considered no elevation changes. The simulations of optimal stop-to-stop trajectories do not model elevation changes.

2.3 Environmental Conditions and HVAC Usage

Environmental temperature and air conditioning (A/C) usage significantly influence energy consumption. Based on meteorological records and operational logs:

- The annual average temperature in Mexico City is approximately 17°C, with seasonal variations from 5°C in winter mornings to 30°C in summer afternoons.
- These buses do not use air conditioning during the operation; therefore, no energy draw during its performance is modeled.
- Passenger density also correlates with HVAC demand, increasing auxiliary power consumption during peak hours.

2.4 Current Data Analysis

Key insights were derived from detailed telemetry and historical route logs:

- Analysis of energy consumption per kilometer.
- Trends in energy saving from regenerative braking (evaluate effectiveness: 38% regen efficiency for the best-case scenario vs 30% for the worst-case scenario).

- Correlation between traffic patterns and battery usage.
- Effect of temperature variations on battery performance.
- Analyzing delays and bottlenecks caused by urban traffic conditions.

2.5 Results and Findings

Simulations applying optimized driving strategies yielded the following results:

- **Energy Savings:**
 - ◇ For 500 m segments, simulated energy consumption ranged between 0.71 kWh/km and 0.87 kWh/km.
 - ◇ For 1000 m segments, simulated energy consumption ranged between 0.62 kWh/km and 0.76 kWh/km.
 - ◇ The current measured real-world energy consumption for these buses is approximately 0.92 kWh/km, based on 2024 telemetry records for the electrified fleet.
 - ◇ Even in the worst-case simulation (shorter segment, higher assumed weight, and less efficient drivetrain), the simulated consumption outperformed current real-world performance.
- **Parameter Sensitivity:**
 - ◇ Lower consumption scenarios were based on total vehicle weight of 22,000 kg, rolling resistance coefficient of 0.006, drivetrain efficiency of 0.95, and regenerative efficiency of 38%
 - ◇ Higher consumption scenarios assumed: 25,000 kg total weight, rolling resistance of 0.008, drivetrain efficiency of 0.90, and regenerative efficiency of 30%.
- **Battery Lifespan Projections:**
 - ◇ Simulated driving cycles that emphasized controlled acceleration and maximized regenerative braking reduced the occurrence of high-current (C-rate) events, contributing to a projected increase in battery cycle life and thermal stability.

3. Conclusion and Recommendations

There are several reasons why the energy optimal stop-to-stop trajectories improve energy efficiency significantly over conventional stop-to-stop trajectories [5]. There are two main components: the shape of the speed

trajectory itself and the exploitation of the efficiency characteristics in the speed-torque diagram. In the latter, the optimal trajectory makes sure that the operating regime of the e-powertrain never remains long in the low efficiency regime that occurs at very low power levels, typical for low speed and low or zero acceleration conditions.

In the former, the optimal trajectory reaches the maximum kinetic energy early on so that it can be used to overcome drag and rolling resistance later at 100% efficiency. In typical speed trajectories, the maximum kinetic energy is reached towards the end of the drive segment and regenerative braking is used to recover some of this energy at relatively low efficiency, typically at 40% or lower. The optimal trajectory recovers a portion of the kinetic energy at 100% efficiency. Both effects contribute to the observed savings that can exceed 30% in certain cases.

Key Takeaways:

- Energy optimization simulations demonstrated that even conservative driving strategies can reduce energy consumption below current real-world levels.
- Stop-to-stop distance plays a critical role: longer segments enable more efficient deceleration and energy recovery.
- Lightweighting and low-resistance tires can further enhance efficiency if adopted alongside driving strategy improvements.

Recommendations for Metrobus Line 3:

- Implement eco-driving training and codify energy-efficient practices for drivers.
- Use time or distance markers between stops along line 3 to aid the driver when to initiate another drive segment. This could easily be done with a GPS unit.
- Promote coasting techniques before stopping to increase regenerative energy capture.
- Prioritize deployment on longer stop-to-stop segments, where energy performance is most efficient.
- Explore procurement strategies focused on reducing total bus mass and improving drivetrain efficiency as well as ensuring actual coasting (without any level of regenerative braking.)

References

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