Bridging the Gap: Boosting EV Range and Fuel Efficiency with an Ethanol Range Extender

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ABSTRACT

The accelerated global push for vehicle electrification faces unique challenges in emerging markets, where infrastructure limitations, autonomy constraints, and cost barriers hinder widespread adoption, particularly in commercial vehicle fleets. As a transitional solution, range extenders powered by renewable fuels present a compelling alternative, enabling electric vehicles to operate beyond the limitations of battery-only architectures while maintaining environmental integrity.

This paper presents the design, integration, and functional validation of a range extender system based on a flex-fuel internal combustion engine operating on ethanol, a locally abundant and low-carbon fuel. Combined with an electric generator and inverter, the system supplies energy to the traction battery without mechanical connection to the drivetrain, allowing for steady-state, high-efficiency operation.

Beyond its modularity and scalability, this architecture can be adapted to a wide range of vehicle platforms and power profiles. The result is a solution that bridges the gap between full electrification and the operational realities of Latin America's commercial transport sector, offering a pragmatic and sustainable path toward decarbonization.

INTRODUCTION

The first quarter of 2025 witnessed a remarkable surge in global battery electric vehicle (BEV) sales, with an impressive year-on-year growth of 42%. This increase propelled the global BEV market share to a record-breaking 16% in Q1 2025 [1], with full-year projections surpassing 20 million units sold globally [2]. While this reflects impressive progress in developed markets, the picture in emerging economies remains fragmented. In Brazil, despite an 89% year-over-year increase, electric vehicles (EVs), including hybrids and electrified models, still accounted for just 6.5% of new vehicle registrations in 2024 [3]. The reasons are clear: charging infrastructure is insufficient, vehicle prices remain high, and range anxiety continues to dominate consumer perception.

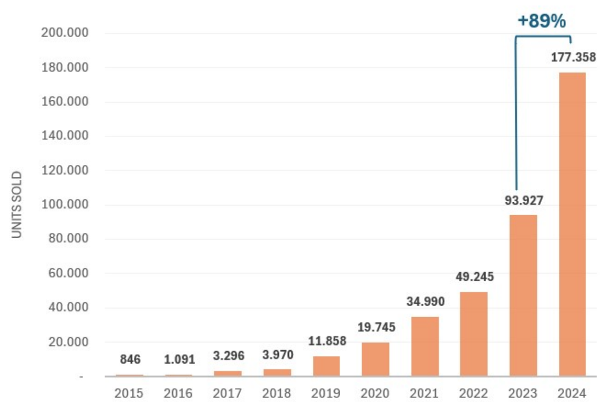

Figure 1. Sales history of electrified vehicles in Brazil. Source: Adaptation [3]

According to ABVE (Brazilian Electric Vehicle Association), nearly 50% of all public chargers are concentrated in the Southeast region, and over 75% of municipalities in Brazil do not yet have a single public EV charging point. Of the 14,827 existing charging stations, 84% (12,397) are slow (AC) chargers, while only 16% (2,430) are fast (DC) [4].

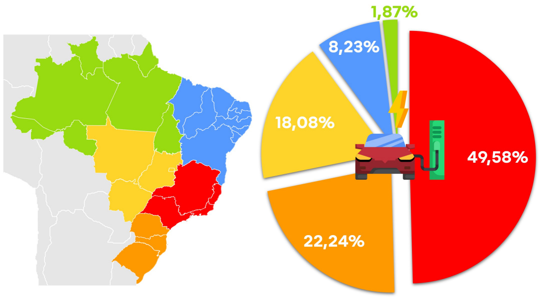

Figure 2. Charges distribution across Brazil's regions.
Source: Adaptation [4]

In fact, a closer look at the data presented in Figure 3 reveals a striking imbalance: nearly 50% of all public charging stations in Brazil are concentrated in just 41 cities, which represent only 0,74% of the country's municipalities. This stark centralization leaves vast regions underserved or completely unassisted. For logistics operators, fleet managers, and users in rural or remote areas, adopting electrification under these conditions is not just challenging, it's often financially unfeasible and operationally impractical.

	City	State	AC (Slow charge)	DC (Fast charge)	Total	MarketShare
1	São Paulo	SP	1.586	155	1.741	11,74%
2	Rio de Janeiro	RJ	774	74	848	5,72%
3	Brasília	DF	397	91	488	3,29%
4	Porto Alegre	RS	252	26	278	1,87%
5	Curitiba	PR	294	94	388	2,62%
6	Goiânia	GO	206	35	241	1,63%
7	Campinas	SP	187	29	216	1,46%
8	Florianópolis	SC	198	22	220	1,48%
9	Fortaleza	CE	190	25	215	1,45%
10	Salvador	BA	178	28	206	1,39%
11	Belo Horizonte	MG	176	24	200	1,35%
12	Recife	PE	152	15	167	1,13%
13	Barueri	SP	112	15	127	0,86%
14	Natal	RN	111	12	123	0,83%
15	Ribeirão Preto	SP	99	19	118	0,80%
16	São José dos Campo	SP	83	35	118	0,80%
17	Maringá	PR	94	15	109	0,74%
18	Uberlândia	MG	53	34	87	0,59%
19	Balneário Camboriú	SC	79	5	84	0,57%
20	Maceió	AL	70	13	83	0,56%
21	Vitória	ES	69	14	83	0,56%
22	Santos	SP	69	12	81	0,55%
23	Gramado	RS	72	8	80	0,54%
24	Londrina	PR	54	24	78	0,53%
25	Joinville	SC	62	12	74	0,50%
26	Blumenau	SC	61	12	73	0,49%
27	Aracaju	SE	67	5	72	0,49%
28	São José do Rio Pret	SP	56	15	71	0,48%
29	Campo Grande	RN	53	14	67	0,45%
30	Guarulhos	SP	55	12	67	0,45%
31	Teresina	PI	50	14	64	0,43%
32	Caxias do Sul	RS	55	8	63	0,42%
33	Niterói	RJ	50	13	63	0,42%
34	João Pessoa	PB	50	12	62	0,42%
35	Campina Grande	PB	43	17	60	0,40%
36	Jundiaí	SP	53	7	60	0,40%
37	Cascavel	CE	45	12	57	0,38%
38	São Luís	MA	37	19	56	0,38%
39	Cuiabá	MT	44	10	54	0,36%
40	Foz do Iguaçu	PR	48	5	53	0,36%
41	São Bernardo do Can	SP	47	6	53	0,36%
		Total	**6.431**	**1.017**	**7.448**	**50,25%**

Figure 3. Charge stations on the 41 cities that account for 50% of all charges in Brazil.
Source: Adaptation [4]

In short: the EV revolution is happening, but not fast enough for everyone, and not everywhere.

In this fragmented scenario, Brazil faces a unique opportunity: to redefine how range, autonomy, and sustainability are delivered, not by copying foreign models, but by embracing local strengths. Charging networks cannot expand overnight. Battery packs alone cannot solve logistics demands. And fleet operators need low-risk, low-cost, and low-carbon alternatives.

There is a clear and urgent challenge: how do we extend the benefits of electrification to segments where EV adoption is currently blocked by cost, autonomy, and infrastructure gaps? And how do we do that without sacrificing environmental responsibility?

This is the call that an Affordable Ethanol Range Extender (REx) responds to.

Some have tried to answer this challenge through traditional detours, but most have failed. Larger battery packs increase both cost and vehicle mass, leading to diminishing returns, especially in fleet applications. Diesel-based Range Extenders, while functional, undermine CO_2 targets and are politically misaligned with green goals. Even gasoline hybrid solutions, imported from other regions, fail to capitalize on Brazil's ethanol infrastructure, one of the most robust and sustainable fuel ecosystems in the world.

What the market needs is not more of the same, it needs a technically elegant, economically viable, and environmentally responsible leap.

Brazil is not starting from scratch. The country has a mature ethanol supply chain, a flex-fuel legacy, and local engineering talent ready to reimagine electrification on its own terms.

FROM PROBLEM TO PROTOTYPE

The Affordable Ethanol Range Extender project was launched as a direct response to Brazil's lagging EV adoption, particularly in light commercial vehicles (LCVs), where autonomy limitations severely compromise viability. The BEV LCV platform of a large OEM was selected specifically due to its low electric-only range (~110 km – 32kWh battery pack) and its market potential for fleet use, positioning it as a real-world proving ground for scalable electrified autonomy.

The range extender operates as an auxiliary power unit, designed to recharge the battery of the electric vehicle while in motion, without any mechanical connection to the wheels. When the battery's state of charge (SOC) reaches a defined threshold, the system activates a compact internal combustion engine, which spins an electric generator. This generator converts the engine's mechanical energy into electrical energy, which is managed by an inverter and directed to either recharge the traction battery or directly supply energy to the vehicle's electrical system. Unlike traditional hybrids, the REx engine never propels the vehicle directly. This allows it to operate at steady RPMs within its optimal efficiency range, significantly reducing fuel consumption and emissions compared to conventional internal combustion engine (ICE) vehicles.

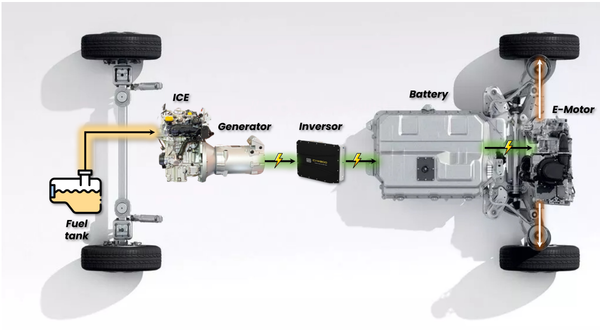

Figure 4. REx architecture.
Source: own authorship

The system was engineered to function as an accessory, fully integrated with the existing OEM BEV architecture, with no physical connection to the drivetrain, enabling seamless post-assembly addition.

Marcopolo recently unveiled Brazil's first hybrid ethanol-powered bus featuring a Range Extender system, with commercial availability expected in 2026. Developed in partnership with Horse and WEG, the vehicle is driven by an electric motor, which is powered by a turbocharged 1.0-liter ethanol engine, ensuring a range of up to 450 km [5].

At the heart of the system lies a HORSE 1.0l 3-cylinder, turbocharged, direct injection, flex-fuel engine (HR10 DDT), optimized to operate on E100 ethanol but fully capable of running on gasoline. This dual-fuel capability maximizes flexibility while still benefiting from ethanol's high knock resistance and cleaner combustion profile. Engine performance reaches 92 kW at 5250 rpm and 220 N.m at 2900 rpm (see Figure 5), with full potential to comply with BIN30 (or even lower) emissions standards under FTP-75 and FTP-74 testing cycles.

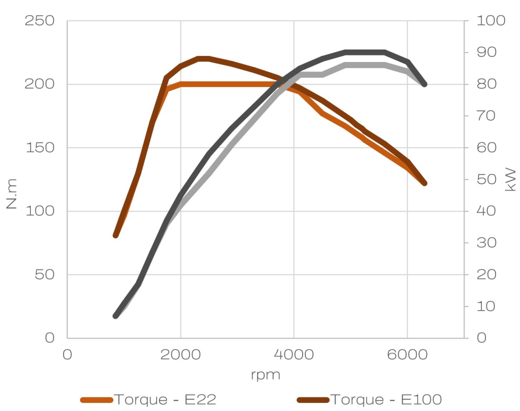

Figure 5. HR10 DDT Power and Torque curve.
Source: own authorship

The major thermal benefit of this architecture comes from operating the engine exclusively in high-efficiency BSFC (Brake Specific Fuel Consumption) zones, avoiding transient conditions common in standard ICE drivetrains. Unlike conventional gasoline-powered ICEs directly connected to wheels (which often run at low loads and high inefficiency), the range extender enables steady-state operation within the optimal torque/RPM island (see Figure 7).

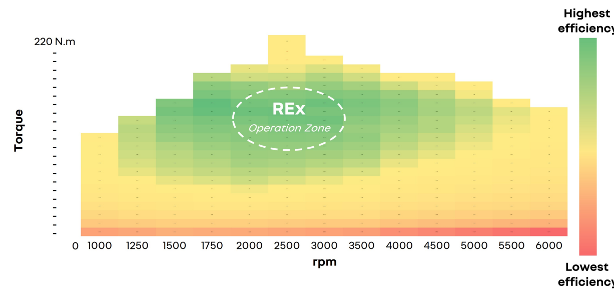

Figure 6. HR10 DDT BSFC.
Source: own authorship

To take advantage of the best BSFC region, the engine must run at 90°C of coolant temperature, and to run the system at this temperature level, a major integration complexity emerged from differing coolant temperature requirements. The ICE operates at a standard 90°C for emissions and fuel efficiency, while the generator and inverter (WEG CVW500G2) require an inlet coolant temperature of 50°C for safe operation. To accommodate this, a dual-loop cooling system was implemented, each with independent pumps, flow regulators, and heat exchangers, validated during dynamic simulations and in-vehicle commissioning.

When running a generator coupled with an ICE, high-frequency magnetic fields emitted by the generator presented risks to surrounding sensor reliability. EMI mitigation required a dedicated test campaign, redesigning cable routing, shielding, and grounding strategies to avoid disturbances in sensor signal acquisition, particularly for critical inputs such as RPM, coolant temperature, and torque sensors. This is a key consideration for any high-voltage generator.

Unlike BEVs, a Range Extender introduces new diagnostic layers for:

- Fuel level monitoring.
- ICE RPM feedback.
- Coolant temperature and pressure.
- Combustion and generator fault codes.

All were integrated into the REx diagnostic bus via CAN, with additional UDS (Unified Diagnostic Services) layers implemented.

The WEG CVW500G2 inverter, paired with a WEG ROD500HSM generator, enables controlled energy conversion up to 75 kW peak, with >94% efficiency between 1400–3000 rpm. The engine is started by the inverter using controlled torque ramp-up, allowing higher starting RPM and eliminating starter motor dependency, a significant emissions advantage at cold starts.

The energy strategy is based on:

- Charge-sustaining logic, maintaining SOC within a pre-defined window.
- Predictive torque mapping, keeping engine load within BSFC optimum.
- Minimal engine-on/off cycling, preserving NVH and mechanical longevity.
- Event-driven startup (e.g., downhill regen disabled when battery full).

This strategy ensures:

- Near-zero transients during engine operation.
- Stable RPM and torque during most cycles.
- Lower cumulative CO_2 and NO_x, as the engine avoids inefficient zones.

These aspects make the Range Extender inherently cleaner than traditional ICEs.

One of the project's most significant achievements is the seamless integration with the OEM BEV, allowing the REx to behave as a true modular accessory. It functions independently of the vehicle's powertrain, connects only via CAN and cooling/fuel lines, and can be removed or serviced without affecting the EV base logic.

VALIDATION

The REx system's architecture was fully validated under AVL's standard verification process. A total of 96 out of 96 control requirements were tested and passed, including:

- Engine start/stop sequencing.
- Fuel pump and relay control.
- Coolant and WEG temperature limits.
- Inverter and generator shutdown thresholds.
- CAN signal consistency and fallback logic.

Each transition of the control state machine, from sleep → wake-up → engine start → power generation → stop → HV disconnect → sleep, was verified both in simulation (MiL with MATLAB R2016b) and in physical testbenches.

In addition, engine stop behavior under regeneration, engine-start overshoot protection, and torque ramp-down during shutdown were validated, ensuring full compliance with safety and control logic expectations for this prototype.

Because the engine operates only within a narrow and optimized BSFC island, and avoids start-stop transients during its active phase, the system opens new possibilities for lowering emissions compared to conventional ICE vehicles:

- Start-up is controlled by the inverter with high starting RPM, reducing cold-start emissions.
- No throttle transients during operation: power demand is regulated via torque request to the generator.
- Load control remains steady thanks to buffer capacity from the traction battery.
- Operating RPM remains within 2200–3000 rpm, avoiding low-efficiency regions .

Once the architecture, energy strategy, and control logic of the Affordable Ethanol Range Extender were defined, the system underwent extensive simulation, bench testing, and on-road validation to assess its efficiency, autonomy, and integration with the LCV platform.

Two major test cycles were applied: the FTP-74 urban cycle and the HWFET highway cycle, tested in Charge Sustaining (CS) modes. The results are shown in the Figure 7.

Vehicle	Test Cycle	Mode	Modeled Fuel Consumption (km/l)	Real-World Fuel Consumption (km/l)	Real-World Fuel Consumption (l/100km)	Energy Intensity (MJ/km)
LCV REx	FTP-74	Charge Sustaining	7,2	7,4	13,5	2,71
LCV REx	HWFET	Charge Sustaining	6,4	6,7	14,9	3,00
LCV Diesel	FTP-75	-	-	10,1	9,9	3,53
LCV Diesel	HWFET	-	-	10,3	9,7	3,46

Figure 7. Test cycles results to REx validation.
Source: own authorship

With a 70-liter fuel tank, the real-world autonomy achieved was substantial.

Urban cycle (FTP-74):

- 504 km with the REx (CS) + 110 km from the base BEV battery = 614 km total range.

Highway cycle (HWFET):

- 448 km with the REx + 110 km from BEV battery = 558 km total range.

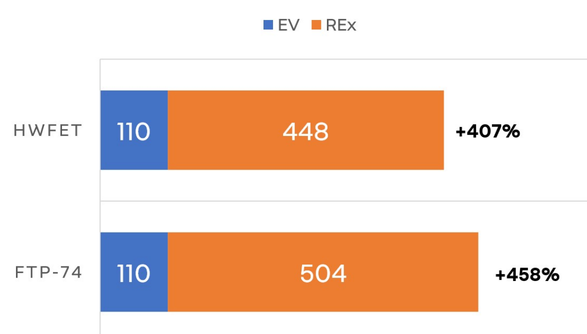

Figure 8. Autonomy reached for FTP74 and HWFET test cycles.
Source: own authorship

This represents an autonomy increase of over 400% compared to the base EV platform operating on battery alone, without any dependency on public charging infrastructure.

These factors position the ethanol-based REx as not only a solution for autonomy, but as a potentially cleaner alternative to traditional ICEs used in urban logistics.

While diesel may initially seem more fuel-efficient in terms of kilometers per liter, a deeper analysis reveals that the Affordable Ethanol REx offers clear advantages in both environmental and economic performance.

In real-world conditions, the vehicles tested show:

- FTP-74: 7.4 km/L (REx) vs 10.1 km/L (Diesel).
- HWFET: 6.7 km/L (REx) vs 10.3 km/L (Diesel).

However, when normalized by energy intensity, the results reverse:

- FTP-74: 2.71 MJ/km (REx) vs 3.53 MJ/km (Diesel).
- HWFET: 3.00 MJ/km (REx) vs 3.46 MJ/km (Diesel).

This efficiency directly affects CO_2 emissions, based on Brazilian fuel emission factors. And to quantify the long-term environmental benefit of the REx architecture, we consider the average usage profile of a light commercial vehicle (LCV) in Brazil:

- Approximately 30.000 km/year, a typical value for delivery fleets and intercity vans.
- Over a 5-year operational cycle, this results in 150.000 km driven per vehicle.

Using the real-world fuel test results:

- LCV REx E100: 77 to 86 gCO_2eq/km.
- Diesel LCV: 285 to 291 gCO_2eq/km.

Applying these numbers:

- LCV Diesel (avg. 288 g/km) → 43.2 tonnes CO_2eq over 5 years.
- LCV REx Ethanol (avg. 81 g/km) → 12.2 tonnes CO_2eq over 5 years.

That's a reduction of 31 tonnes of CO_2eq per vehicle. For fleet operators managing dozens or hundreds of LCVs, the potential cumulative impact is transformative. This illustrates how the REx solution not only closes the autonomy gap for electrification in emerging markets, but also acts as a viable decarbonization pathway using existing ethanol infrastructure.

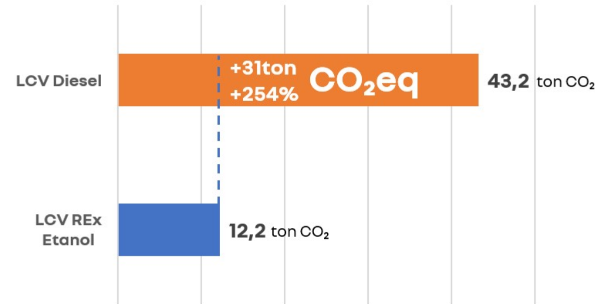

Figure 9. CO2 emisson of usual LCV Diesel and LCV with REx system driven 150k km.
Source: own authorship

On the economic side, fuel pricing is decisive:

Fuel Type	Average Price (R$/l)	Real-World Consumption (l/100km)	Fuel Cost per 100km
Ethanol	4,09	15,6	**R$ 63,81**
Diesel	6,29	9,8	**R$ 61,73**

Figure 10. Economic perspective of LCV fueled with ethanol and diesel.
Source: own authorship

Over 150,000 km:

- Ethanol REx fuel cost: R$95,709.83
- Diesel LCV fuel cost: R$92.590,78

In other words, the REx delivers:

- Lower energy intensity.
- Substantially lower CO_2eq emissions.
- Competitive fuel cost per kilometer.

All while leveraging Brazil's existing ethanol infrastructure, with no reliance on grid capacity or charging downtime, making it a strategically superior choice for fleet electrification in emerging markets.

CONCLUSION

After overcoming technical, logistical, and environmental challenges, the Affordable Ethanol Range Extender proves itself not only as a functional system, but as a scalable one also. The project reaches a maturity where it can return to the broader industry landscape, not as an experiment, but as a deployable innovation, as already adopted by main players, like Marcopolo.

By combining a flex-fuel ICE, a high-efficiency generator, and a smart inverter, the REx offers comparable autonomy, lower CO_2eq emissions, and competitive TCO when compared to diesel platforms, particularly when powered by Brazil's abundant and low-carbon ethanol.

One of the system's greatest strengths lies in its scalability and tailored solution. The powertrain package (ICE + generator + inverter) can be re-dimensioned and calibrated for a wide range of use cases, from small urban delivery vans to medium-duty trucks and even stationary applications. This flexibility allows manufacturers and integrators to adapt the REx core to different power and range requirements, without rebuilding the energy logic or control structure from scratch.

In summary, the REx doesn't replace the EV, it completes it. It offers a bridge between full electrification and the real-world constraints of Latin America's mobility landscape. By combining local fuels, intelligent control, and proven integration capability, the project delivers a genuine elixir: a technology that is ready to scale, ready to adapt, and ready to decarbonize.

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