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Decarbonizing Motorcycle-Based Last-Mile Delivery in Jakarta: A Jakarta-Calibrated Scenario Simulation of Routing, Consolidation, and Fleet Electrification

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Abstract. Urban last-mile delivery is increasingly shaped by e-commerce growth, rapid-delivery expectations, and motorcycle-based courier operations. Jakarta is a relevant setting because motorcycles dominate road traffic and two-wheelers are widely used for last-mile delivery. This study develops a Jakarta-calibrated scenario simulation to estimate operational carbon dioxide (CO2) emissions under alternative combinations of route optimization, micro-hub consolidation, pickup-point delivery, and electric-motorcycle adoption. The model represents an illustrative 500-courier fleet only as a scaling device; daily courier distance is calibrated at 70 km/day, the midpoint of the 60-80 km/day range reported for Indonesian two-wheeler last-mile couriers, and 300 operating days/year is treated as an analytical normalization rather than an observed company schedule. Baseline emissions are therefore also reported per courier-year. Scenario VKT reductions are literature-informed inputs rather than outputs of an independently solved Vehicle Routing Problem or GIS model. To avoid double counting in the integrated scenario, individual distance-reduction effects are compounded and constrained by an explicit 40% VKT-reduction cap. Electric-motorcycle electricity use is set at 0.025 kWh/km, with a 10% charging-loss allowance, and electricity emissions are calculated using a Jakarta-relevant Java-Madura-Bali (JAMALI) grid factor of 0.87 kg CO2/kWh. Under the calibrated baseline, the illustrative fleet travels 10.50 million km/year, consumes 300,000 L of gasoline, and emits 693.0 tCO2/year (1.386 tCO2 per courier-year). Conditional on the scenario inputs, route optimization, micro-hub batching, and pickup-point consolidation correspond to 12.0%, 18.0%, and 25.0% lower emissions, respectively. A route-optimization plus 40% electric-motorcycle scenario produces an estimated 38.9% reduction, while the integrated scenario produces an estimated 62.9% reduction and 70.8% lower energy expenditure. These values should be interpreted as scenario-contingent estimates, not observed treatment effects. The analysis indicates that reducing avoidable vehicle-kilometers before electrifying the remaining travel is a promising decarbonization sequence for motorcycle-dominant urban delivery systems.

Keywords: Green Logistics, Last-Mile Delivery, Motorcycle Courier, Scenario Simulation, Vehicle-Kilometers Travelled, Electric Motorcycle.

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1 Introduction

The last-mile segment is often the most operationally complex and environmentally sensitive part of the logistics chain because deliveries are fragmented, spatially dispersed, and exposed to traffic delay, failed delivery attempts, kerbside access constraints, and increasing customer expectations for rapid fulfillment. The literature consistently describes last-mile logistics as a major source of negative externalities, including congestion, air pollution, greenhouse-gas emissions, noise, and inefficient vehicle utilization [7], [8], [2].

The issue is particularly relevant for Indonesia because urban parcel demand is linked to the rapid expansion of the digital economy and e-commerce. The e-Conomy SEA 2024 report indicates that Southeast Asia's digital economy continued to grow in 2024, with e-commerce reaccelerating by approximately 15% year-on-year and video commerce accounting for a growing share of online retail activity [9]. This demand growth has direct implications for delivery frequency, courier utilization, vehicle-kilometers travelled, and the need for low-emission urban freight strategies.

Jakarta is a strategic setting for examining motorcycle-based green logistics. BPS-Statistics DKI Jakarta Province recorded 9,167,512 registered motorcycles in 2024, while TomTom reported a 2025 average congestion level of 59.8% and an average 10-km travel time of 26 minutes and 19 seconds in Jakarta [13], [4]. A 2025 regional two-wheeler last-mile delivery study based on published reports and industry-stakeholder interviews further reported that motorcycles account for approximately 60% of logistics activities in Indonesia and that couriers travel about 60-80 km per day [17]. These data provide an empirical basis for calibrating the model to a motorcycle-dominant, congestion-intensive operating environment rather than to a named courier company.

At the policy level, Indonesia's Enhanced Nationally Determined Contribution increased its 2030 mitigation target to 31.89% unconditionally and 43.20% conditionally relative to business as usual, and Indonesia subsequently submitted its Second NDC to the UNFCCC in October 2025 [11], [19]. These national commitments strengthen the relevance of translating climate ambition into operational strategies for urban freight and last-mile delivery.

Existing research provides strong conceptual support for last-mile decarbonization, but important gaps remain for motorcycle-dominant cities. Much of the published evidence evaluates vans, light goods vehicles, cargo bikes, lockers, or urban consolidation in non-Indonesian settings, while the recent Southeast Asian evidence base identifies limited standardized data for two-wheeler last-mile delivery and substantial variation in company-level sustainability reporting [17]. The present study therefore does not claim company-specific causal effects; instead, it tests a transparent set of Jakarta-calibrated scenarios that can be replaced by operator GPS, order, fuel, and charging records when such data become available.

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Table 1. Research gap and contribution matrix

Gap type	Problem in prior literature	Contribution of this study
Geographic gap	Published evidence is geographically concentrated and Southeast Asian two-wheeler LMD data remain limited and heterogeneous [17].	Jakarta-calibrated scenario simulation using BPS, traffic, and Indonesian two-wheeler courier evidence.
Vehicle gap	Many studies emphasize vans, trucks, or cargo bikes.	Focuses on gasoline and electric motorcycles, with results normalized per courier-year.
Intervention gap	Many studies assess interventions separately; integrated assumptions can create overlap or double counting.	Uses explicit compounded effects and a conservative integrated VKT cap to handle interaction.
Managerial gap	Emission models often omit energy-cost implications.	Calculates operational CO2 and energy expenditure while clearly excluding full total cost of ownership.

The contribution of this paper is fourfold. First, it reframes Jakarta last-mile delivery as a motorcycle-dominant urban logistics problem using an empirically calibrated daily-distance range. Second, it distinguishes scenario inputs from modeled outcomes so that assumed VKT reductions are not misinterpreted as independently estimated intervention effects. Third, it introduces an explicit overlap constraint for the integrated intervention package and includes charging losses in the electric-motorcycle calculation. Fourth, it reports fleet-level and per-courier outcomes, together with sensitivity analyses, to improve transferability and transparency for operators and policy makers.

This study asks: under explicitly stated and empirically bounded assumptions, how would operational CO2 emissions change if a Jakarta motorcycle-courier fleet adopted route optimization, spatial consolidation, pickup-point delivery, and partial electrification? The design is therefore termed a Jakarta-calibrated scenario simulation, not a proprietary-company case study. Its purpose is comparative and decision-analytic: the model estimates conditional outcomes under specified inputs rather than claiming observed causal effects from real-world interventions.

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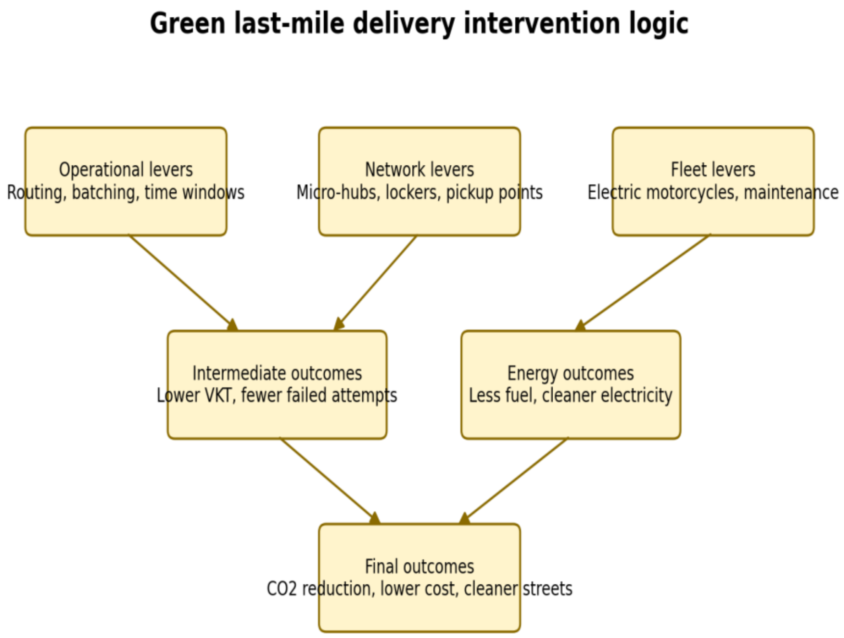

Fig. 1. Conceptual framework linking green logistics interventions to emission and cost outcomes

2 Literature Review

2.1 Sustainable urban last-mile logistics

Sustainable last-mile logistics is commonly understood as a multidimensional problem that requires balancing environmental, economic, and social outcomes. Silva et al. [2] reviewed 102 articles and identified multiple clusters of solutions, including vehicular solutions, operational solutions, and organizational solutions. Their findings emphasize that no single last-mile solution is universally optimal, because outcomes depend on urban form, delivery density, infrastructure, stakeholder incentives, and customer behavior [2].

Ranieri et al. [7] classify last-mile innovation into categories such as innovative vehicles, proximity stations, collaborative logistics, routing optimization, and public-policy interventions. This classification is useful for Jakarta because courier emissions cannot be reduced only by changing vehicle technology; the spatial structure of delivery, the timing of demand, and customer-delivery interfaces also shape total VKT and emissions [7].

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2.2 E-commerce demand, fragmentation, and delivery inefficiency

E-commerce growth increases the frequency and fragmentation of parcel movements, and rapid-delivery competition can reduce vehicle utilization. Allen et al. [8] show that last-mile parcel operations can suffer from poor utilization and duplicated service areas as carriers compete to meet exacting customer expectations. This phenomenon is relevant to Jakarta, where app-based courier services, marketplace deliveries, instant commerce, food delivery, and same-day services can overlap spatially and temporally.

Global scenario work by the World Economic Forum suggests that last-mile delivery demand could rise sharply by 2030, potentially increasing delivery vehicles and urban delivery emissions without effective intervention. The report identifies interventions such as electric vehicles, dynamic rerouting, and parcel lockers as key options for reducing both congestion and CO_2 emissions [1].

2.3 Motorcycle courier emissions and electrification

Motorcycle fuel use and emissions vary with vehicle age, mileage, regulatory class, load, maintenance, and traffic conditions. Tsai et al. [5] reported fuel-economy values around 29.5-34.7 km/L across investigated motorcycle regulatory phases. Because these observations are not Jakarta courier measurements, the present model uses a rounded 35 km/L central value and evaluates 30-50 km/L in sensitivity analysis rather than treating one value as universally representative.

Electric motorcycles have zero tailpipe CO_2 emissions but non-zero electricity-related emissions. The Asian Development Bank's Electric Motorcycle Charging Infrastructure Road Map for Indonesia uses an average electric-motorcycle electricity consumption of 0.025 kWh/km [18]. The present model applies that Indonesia-specific value and adds a 10% charging-loss allowance, yielding 0.0275 kWh drawn from the grid per vehicle-kilometer. For Jakarta, electricity emissions are evaluated using a JAMALI grid factor of 0.87 kg CO_2/kWh, with lower and higher grid-intensity values tested in sensitivity analysis. This makes the electric-motorcycle calculation location-relevant while acknowledging that grid intensity changes over time.

Table 2. Selected literature matrix

Source	Design/context	Key finding	Use in this paper
Silva et al. [2]	Systematic review of sustainable urban last-mile logistics	Last-mile solutions need multi-dimensional evaluation; no universal solution exists.	Supports integrated portfolio approach.
Ranieri et al. [7]	Review of last-mile innovations to reduce externalities	Innovations include vehicles, proximity points, collaboration, routing, and policy.	Basis for intervention categories.
Allen et al. [8]	London case study	E-commerce creates	Justifies demand-

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	of e-commerce and last-mile vehicles	utilization and duplication challenges.	fragmentation focus.
Tsai et al. [5]	Motorcycle fuel economy and emissions	Fuel economy and emissions vary by mileage and regulatory phase.	Supports fuel-economy sensitivity analysis.
World Economic Forum [1]	Global last-mile ecosystem report	Urban last-mile demand and emissions could rise without interventions.	Provides strategic framing for EVs, rerouting, and lockers.
ITDP Indonesia / Clean Mobility Collective [17]	Regional two-wheeler last-mile delivery study using reports and industry interviews	Indonesian couriers travel about 60-80 km/day; motorcycles account for ~60% of logistics activity.	Empirical calibration of daily courier distance and motorcycle-dominant context.
Asian Development Bank [18]	Indonesia electric-motorcycle charging infrastructure road map	Average electric-motorcycle electricity consumption of 0.025 kWh/km.	Indonesia-specific EV energy-intensity input; 10% charging losses added transparently.

3 Methodology

3.1 Study design

This research uses a Jakarta-calibrated scenario-simulation design. The modeled fleet of 500 couriers is an illustrative scaling parameter, not an observed workforce of a specific company. The primary reporting unit is therefore both fleet-year and courier-year. The model is intentionally transparent and replaceable: if an operator supplies GPS traces, order-level records, fuel receipts, delivery-attempt data, and charging records, the same equations can be recalculated with proprietary observations. The study does not estimate causal treatment effects and does not solve an original Vehicle Routing Problem (VRP) or GIS network optimization; instead, it quantifies conditional emission outcomes under literature-informed scenario inputs.

3.2 Jakarta calibration and baseline normalization

Jakarta was selected because it combines high motorcycle ownership, severe congestion, and intensive two-wheeler delivery activity. BPS recorded 9.17 million registered motorcycles in DKI Jakarta in 2024 [13], while TomTom reported a 59.8% average congestion level in 2025 [4]. More importantly for baseline calibration, the 2025 Southeast Asian two-wheeler LMD study reports that Indonesian couriers travel approximately 60-80 km/day [17]. The model therefore uses 70 km/courier/day as the midpoint central estimate and examines lower and upper values in sensitivity analysis.

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The 300-day operating year is an analytical normalization equivalent to approximately six operating days per week for 50 weeks; it is not presented as an empirically observed company schedule. Fleet size is likewise scalable, so percentage reductions are invariant to whether the model represents 100, 500, or 1,000 otherwise identical couriers.

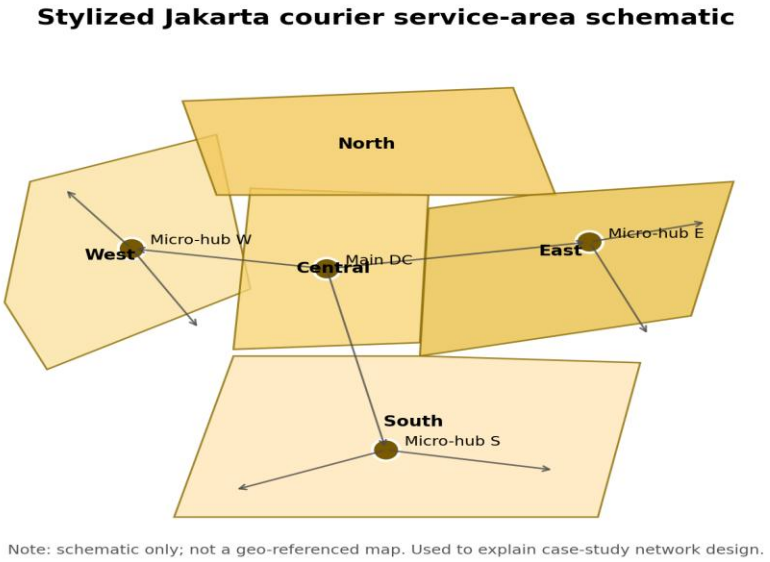

Fig. 2. Stylized Jakarta courier network schematic showing main distribution center, micro-hubs, and zone-based dispatch logic.

3.3 Baseline parameters and empirical status

Table 3 explicitly distinguishes empirically calibrated parameters, literature-derived technical parameters, and analytical scenario assumptions. This distinction addresses the mechanical nature of deterministic scenario models: absolute emissions depend on baseline VKT, while percentage reductions for gasoline-only scenarios follow directly from their assigned VKT levels. Accordingly, the manuscript refers to these results as conditional modeled outcomes and not as independent empirical estimates.

Table 3. Model assumptions and source basis

Parameter	Base value	Explanation	Source basis
Fleet size	500 couriers	Illustrative scaling parameter; results also reported per courier-year	Analytical scenario; not a company observation
Daily distance	70 km/courier/day	Midpoint of reported Indonesian courier range 60-80 km/day	ITDP/Clean Mobility Collective [17]

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Working days	300 days/year	Analytical operating-year normalization (~6 days/week x 50 weeks)	Analytical normalization
Baseline annual VKT	10,500,000 km/year	Fleet x km/day x operating days	Calculated
Gasoline fuel economy	35 km/L	Rounded central value; sensitivity 30-50 km/L	Tsai et al. [5]; sensitivity-bounded
Gasoline CO2 factor	2.31 kg CO2/L	Combustion-based conversion	IPCC [3], derived
Electric motorcycle traction use	0.025 kWh/km	Indonesia road-map average	ADB [18]
Charging loss	10%	Grid draw = 0.0275 kWh/km; sensitivity acknowledged	Analytical assumption
JAMALI grid emission factor	0.87 kg CO2/kWh	Jakarta-relevant base case; sensitivity 0.70-0.95	Indonesia/JAMALI grid factor; [20]
Gasoline price	IDR 10,000/L	Energy-expenditure estimate only	Scenario value
Electricity tariff	IDR 1,500/kWh	Energy-expenditure estimate only	Scenario value

3.4 Scenario construction and interaction handling

The VKT reductions assigned to S1-S3 are literature-informed scenario inputs chosen to represent plausible operational improvement magnitudes; they are not outputs from an original routing algorithm. The integrated scenario is not constructed by adding 12% + 18% + 25%. Instead, potential distance-reduction effects are first compounded as R_raw = 1 - [(1-r_route)(1-r_hub)(1-r_pickup)], which yields a gross theoretical reduction if each effect operated sequentially. Because routing, hubs, and pickup points can act on overlapping kilometers, the effective integrated reduction is constrained by R_S5 = min(R_cap, R_raw), where R_cap = 0.40 in the base case. Thus VKT_S5 = VKT_0(1-R_S5). The 40% cap is deliberately lower than both the arithmetic sum (55%) and the independently compounded gross effect (~45.9%), providing an explicit conservative overlap adjustment rather than assuming full additivity.

$$R\_raw = 1 - [(1-r\_route)(1-r\_hub)(1-r\_pickup)];\ \ R\_S5 = \min(R\_cap, R\_raw);$$
$$VKT\_S5 = VKT\_0(1-R\_S5)$$

For S5, the base-case cap is 40% VKT reduction; sensitivity analysis also evaluates 30% and 35% caps. The resulting estimates should therefore be interpreted as a bounded scenario envelope rather than as a forecast of a specific operator's realized savings.

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3.5 Emission and electricity calculation

Operational emissions are calculated separately for gasoline and electric travel. Gasoline emissions equal gasoline VKT divided by fuel economy and multiplied by the gasoline CO2 factor. Electric emissions equal electric VKT multiplied by traction electricity consumption, a charging-loss multiplier, and the grid factor. The model uses 0.025 kWh/km from the ADB Indonesia road map [18] and a 10% charging-loss allowance, producing 0.0275 kWh/km of grid electricity. A JAMALI grid factor of 0.87 kg CO2/kWh is used for the Jakarta base case, with sensitivity values of 0.70 and 0.95 kg CO2/kWh. The calculation estimates operational emissions only and excludes vehicle and battery manufacturing, infrastructure construction, and customer pickup travel.

Table 4. Scenario definitions and interpretation of mitigation inputs

Code	Strategy	VKT level	Electric share	Operational description
S0	Baseline gasoline motorcycle operation	100% of baseline	0%	Reference condition; no mitigation.
S1	Route-optimization adoption scenario	88% of baseline	0%	12% VKT reduction is a scenario input, not an independently solved VRP result.
S2	Micro-hub and zone-batching scenario	82% of baseline	0%	18% VKT reduction is a literature-informed scenario input.
S3	Pickup-point / parcel-locker scenario	75% of baseline	0%	25% VKT reduction is a literature-informed scenario input; customer pickup travel excluded.
S4	Route optimization + 40% electric motorcycles	82% of baseline	40%	Distance reduction plus partial electrification; EV emissions include charging losses and JAMALI grid electricity.
S5	Integrated green logistics package	60% of baseline	60%	Integrated VKT reduction capped at 40% to account for overlap; no additive stacking of individual percentages.

4 Result

4.1 Calibrated baseline emissions

Using the calibrated central estimate of 70 km/courier/day, 500 illustrative couriers, and 300 normalized operating days, baseline VKT equals 10,500,000 km/year. At 35 km/L, gasoline consumption is 300,000 L/year and operational emissions are 693.0

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tCO_2/year. Normalized per courier, this equals 21,000 km, 600 L gasoline, and 1.386 tCO_2 per courier-year. Because fleet size is a linear scaling parameter, a 100-courier operation with otherwise identical activity would emit one-fifth of the fleet total while retaining the same percentage scenario reductions. The baseline should therefore be interpreted as a calibrated reference condition rather than a measurement of a named platform [17], [5].

Table 5. Conditional modeled emission outcomes by scenario

Scenario	Strategy	Annual VKT	Gasoline L/year	Electricity kWh/year	CO2 t/year	Reduction
S0	Baseline gasoline motorcycle operation	10,500,000	300,000	0	693	0.0%
S1	Route-optimization adoption scenario	9,240,000	264,000	0	610	12.0%
S2	Micro-hub and zone-batching scenario	8,610,000	246,000	0	568	18.0%
S3	Pickup-point / parcel-locker scenario	7,875,000	225,000	0	520	25.0%
S4	Route optimization + 40% electric motorcycles	8,610,000	147,600	94,710	423	38.9%
S5	Integrated green logistics package	6,300,000	72,000	103,950	257	62.9%

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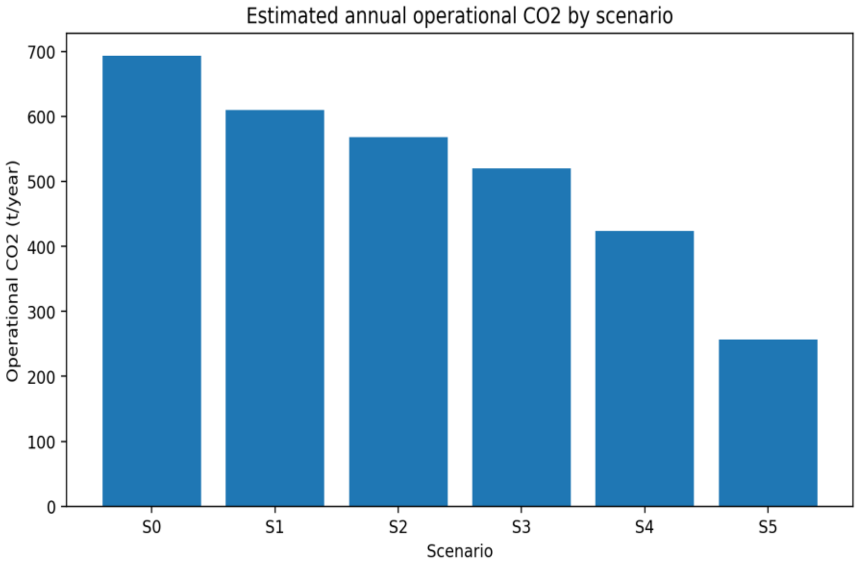

Fig. 3. Estimated annual operational CO2 emissions by scenario

4.2 Conditional mitigation outcomes

For gasoline-only S1-S3, the reported percentage emission changes are mechanically equal to the assigned VKT reductions because fuel economy and the gasoline emission factor are held constant. Thus, the 12.0%, 18.0%, and 25.0% values are conditional scenario outcomes, not independently estimated treatment effects. Under these assumptions, annual emissions are 609.8 tCO2 for S1, 568.3 tCO2 for S2, and 519.8 tCO2 for S3. Their purpose is comparative: they show how much operational CO2 would change if the corresponding VKT reductions were achieved in practice.

When electrification is added, the emission response is no longer identical to the VKT input because gasoline travel is partially replaced by electricity-related emissions. S4 is estimated at 423.4 tCO2/year, 38.9% below baseline. S5 is estimated at 256.8 tCO2/year, 62.9% below baseline, conditional on a 40% integrated VKT cap and 60% electric share. The result reflects two distinct mechanisms: avoiding vehicle-kilometers first and lowering the carbon intensity of the kilometers that remain. These modeled values should not be interpreted as realized savings for any specific Jakarta operator.

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Table 6. Estimated annual energy-expenditure impact

Scenario	Strategy	Estimated annual energy cost (million IDR)	Energy-cost saving
S0	Baseline gasoline motorcycle operation	3,000.0	0.0%
S1	Route-optimization adoption scenario	2,640.0	12.0%
S2	Micro-hub and zone-batching scenario	2,460.0	18.0%
S3	Pickup-point / parcel-locker scenario	2,250.0	25.0%
S4	Route optimization + 40% electric motorcycles	1,618.1	46.1%
S5	Integrated green logistics package	875.9	70.8%

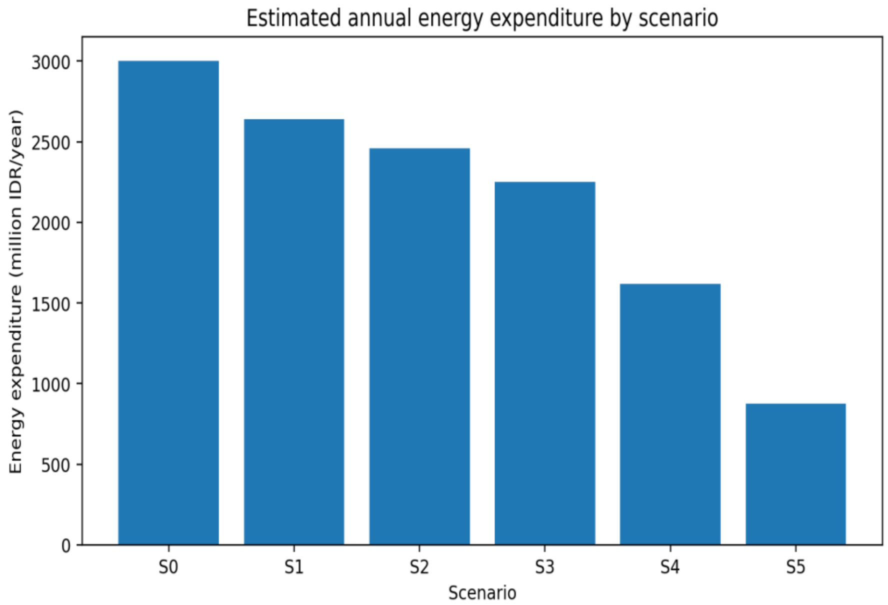

Table 7. Figure 4. Estimated annual energy expenditure by scenario

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4.3 Sensitivity analysis

Sensitivity analysis evaluates parameters that materially influence the electrification result. Fuel economy is varied from 30 to 50 km/L and JAMALI/grid intensity from 0.70 to 0.95 kg CO2/kWh while electric traction use remains 0.025 kWh/km plus 10% charging losses. Across these combinations, the integrated S5 scenario produces estimated operational-emission reductions of approximately 55.6%-67.0% relative to the corresponding gasoline baseline. The direction of the result is therefore stable, although its magnitude remains parameter-dependent.

Table 8. Sensitivity of integrated scenario to fuel economy and grid emission factor

Fuel economy km/L	Grid EF kg CO2/kWh	Baseline CO2 t/y	Integrated CO2 t/y	Reduction
30	0.70	808.5	266.8	67.0%
30	0.87	808.5	284.5	64.8%
30	0.95	808.5	292.8	63.8%
35	0.70	693.0	239.1	65.5%
35	0.87	693.0	256.8	62.9%
35	0.95	693.0	265.1	61.7%
50	0.70	485.1	189.2	61.0%
50	0.87	485.1	206.9	57.4%
50	0.95	485.1	215.2	55.6%

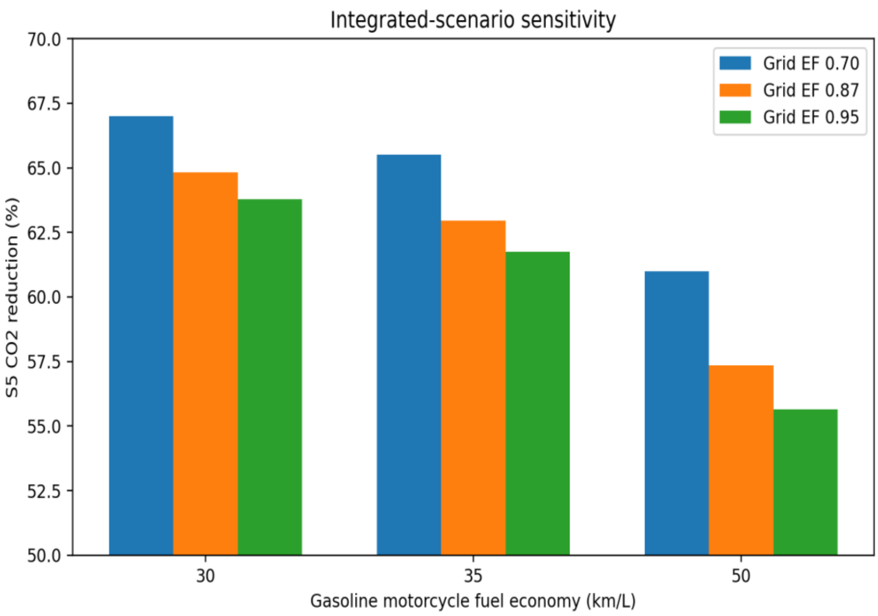

Fig. 4. Sensitivity of integrated-scenario CO2 reduction to fuel economy and JAMALI/grid emission factor

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4.4 Interaction and baseline-distance checks

The integrated VKT cap was varied from 30% to 40% to test whether the main conclusion depends on the upper-bound overlap assumption. With a 60% electric share, a 30% VKT reduction yields approximately 59% lower operational CO_2, a 35% reduction yields about 62%, and the 40% base-case cap yields about 63%. In addition, changing daily distance within the empirically reported 60-80 km/day range changes absolute annual emissions proportionally but does not alter percentage reductions when scenario shares are held constant. This confirms that fleet size and baseline distance mainly scale absolute emissions, whereas intervention assumptions and EV/grid parameters determine relative reductions.

5 Discussion

5.1 Interpretation of the main finding

The main interpretation is not that any one intervention has a proven Jakarta-specific effect of exactly 12%, 18%, or 25%. Rather, the simulation shows how emissions respond when plausible VKT reductions are achieved and how this response changes once gasoline kilometers are partially electrified. This distinction is important because deterministic gasoline-only calculations necessarily map VKT reductions one-to-one into CO_2 reductions. The more policy-relevant insight is the decomposition of the integrated strategy into an activity effect (fewer kilometers) and an intensity effect (lower emissions per remaining kilometer).

Under the base assumptions, a gasoline motorcycle emits approximately 66.0 gCO_2/km from direct fuel combustion (2.31 kg CO_2/L divided by 35 km/L). An electric motorcycle drawing 0.0275 kWh/km from the grid at 0.87 kg CO_2/kWh produces approximately 23.9 gCO_2/km of operational electricity emissions. Thus electrification lowers operational emissions per kilometer, but route and network efficiency remain essential because every avoided kilometer removes both energy use and exposure to congestion. The practical sequence suggested by the model is therefore: avoid unnecessary kilometers first, then electrify the kilometers that remain.

5.2 Managerial implications for courier operators

Courier companies can use the framework as a sensitivity-based decision tool rather than as a forecast. Route optimization is operationally attractive because it can be piloted without major fixed infrastructure, but its realized VKT effect should be verified from pre/post GPS traces. Micro-hubs and pickup points should similarly be evaluated using delivery density, failed-attempt rates, and customer access behavior before scaling. Electric motorcycles are most defensible on high-utilization routes where charging or battery swapping is reliable. Company decisions should be based on measured local effects, not on the central scenario percentages used here.

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5.3 Policy implications for Jakarta

For city planners, the analysis supports coordinated attention to micro-hub zoning, charging and battery-swap access, pickup-point integration, curb management, and platform-data availability. Jakarta-relevant grid emissions should also be updated periodically because the climate benefit of electric delivery fleets changes with JAMALI generation intensity. The scenario framework is therefore best viewed as an adaptive planning model whose technical parameters should be refreshed as official grid and operator data improve.

5.4 Environmental interpretation

The environmental interpretation remains operational rather than life-cycle based. Electric motorcycles shift emissions from the tailpipe to electricity generation, and this study explicitly includes charging losses and a JAMALI grid factor but not battery manufacturing. Pickup points may reduce courier VKT while increasing customer travel if parcels are collected by dedicated motorized trips. Future empirical validation should therefore combine courier GPS traces, parcel-level delivery records, customer pickup-mode surveys, battery life-cycle data, and time-matched electricity factors.

Table 9. Implementation roadmap for Jakarta motorcycle courier decarbonization

Time horizon	Recommended action	Lead stakeholder	Expected outcome
0-3 months	Collect courier GPS traces, order-level delivery logs, fuel receipts, failed-attempt records, and charging data.	Operator	Replace scenario baseline with observed Jakarta operating data.
3-6 months	Pilot route optimization and estimate pre/post VKT change using matched operational periods.	Operator/platform	Empirically estimate routing effect instead of assuming a fixed percentage.
6-12 months	Pilot micro-hubs and pickup points; measure overlap, delivery density, and customer pickup travel.	Operator + local partners	Estimate net VKT effect and interaction among interventions.
12-24 months	Electrify high-utilization routes and meter grid electricity/battery-swap energy.	Operator + EV provider	Obtain observed kWh/km, charging losses, and cost data.
24+ months	Scale only interventions with verified emission	Operator + city government	Evidence-based integrated urban-freight

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	and service benefits; update JAMALI grid factor annually.		decarbonization.

First, the study is a Jakarta-calibrated scenario simulation, not an empirical case study of a named courier company. Daily distance is bounded by Indonesian two-wheeler LMD evidence, but the 500-courier fleet and 300-day operating year are analytical scaling/normalization choices. Absolute totals should therefore be rescaled for actual operators; per-courier results are provided to facilitate this.

Second, S1-S3 VKT reductions are literature-informed scenario inputs rather than results from an original VRP, GIS network model, or controlled intervention. The manuscript now states this explicitly and interprets the associated percentage emission reductions as conditional outcomes. Future work should estimate intervention effects directly from route-level before/after data or optimization experiments.

Third, interaction among routing, micro-hubs, and pickup points is represented by compounded effects with an explicit 40% VKT cap to reduce double counting. This is more conservative than simple addition but remains a modeling assumption. Future studies should estimate interaction terms from operator data or joint network-optimization models.

Fourth, the electric-motorcycle calculation includes an Indonesia-specific traction-energy input, a 10% charging-loss allowance, and a Jakarta-relevant JAMALI grid factor, but it excludes battery production, vehicle manufacturing, infrastructure construction, and time-of-day marginal electricity effects. Finally, the financial analysis covers energy expenditure only; it is not a total-cost-of-ownership analysis and excludes vehicle acquisition, battery replacement, maintenance, software, micro-hub rent, and customer-service impacts.

6 Conclusion

This study presents a Jakarta-calibrated scenario simulation for motorcycle-based last-mile delivery decarbonization. Using a 70 km/day central courier-distance estimate grounded in Indonesian two-wheeler LMD evidence, the illustrative 500-courier baseline equals 10.50 million VKT, 300,000 L of gasoline, and 693.0 tCO_2/year, or 1.386 tCO_2 per courier-year. The 12%, 18%, and 25% reductions associated with S1-S3 are explicitly conditional on the assigned VKT inputs and should not be interpreted as independently estimated empirical effects.

With electrification, the model estimates a 38.9% reduction for S4 and a 62.9% reduction for the integrated S5 scenario, conditional on the stated 40% VKT cap, 60% electric share, 0.025 kWh/km traction demand, 10% charging losses, and 0.87 kg CO_2/kWh JAMALI grid factor. Sensitivity analysis confirms that the direction of benefit persists across plausible fuel-efficiency and grid-intensity values, although the exact magnitude changes. The central managerial implication is sequential: reduce avoidable vehicle-kilometers through routing and consolidation, then electrify the

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remaining travel. Future validation should replace scenario inputs with observed Jakarta courier GPS, order, fuel, customer-pickup, and charging data.

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Conflict of Interest
The authors declare no conflict of interest.

Data Availability
The numerical dataset is a reproducible scenario dataset generated from the parameters reported in Table 3 and Table 4. The model is designed so that fleet size, daily VKT, fuel economy, intervention effects, EV share, charging loss, and grid factor can be replaced with observed operator-specific values without changing the calculation structure.

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