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TEMPORAL AND VEHICLE IMPACTS ON DELIVERY EMISSIONS IN URBAN LOGISTICS: A CASE STUDY OF ROME

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Emerging challenges in urban logistics underscore the need for delivery strategies that balance efficiency with environmental responsibility. This study develops a time dependent delivery model using operational data from a beverage logistics company in Rome, utilizing light commercial vehicles (LCVs) differentiated by fuel type (diesel, petrol) and Euro emission standard (Euro 4–Euro 6). We segment daily operations into four time windows: morning, afternoon, evening, and night, to capture the variability of traffic congestion. For each period, we use a congestion factor calibrated by comparing free-flow and congested travel times retrieved from a routing service. These factors adjust the baseline travel times for realistic routing scenarios. Delivery plans are generated for each time window and vehicle configuration, with calculations for both travel time and emissions. Emissions are estimated using the COPERT methodology, employing standardized emission factors based on euro norms and fuel types. By comparing emission out-comes across time slots and vehicle types, we identify delivery schedules and fleet compositions that minimize environmental impact while maintaining acceptable service levels. The findings demonstrate significant variability in emissions across different delivery time slots, with peak congestion periods showing notably higher emission costs, reaching up to €4.10 per delivery route compared to €1.14 during nighttime operations with advanced vehicle technology. Specifically, shifting delivery schedules from morning to night reduces total emissions by approximately 25.57%, highlighting nighttime deliveries as one of the most effective strategies for mitigating environmental impacts. Additionally, the analysis underscores the importance of fleet composition, revealing that advanced diesel LCVs adhering to the Euro 6d-temp standard equipped with DPF+SCR significantly outperform conventional diesel vehicles, achieving emission reductions up to 63.4%. These insights establish a data-driven foundation for optimizing both temporal scheduling and vehicle selection, enabling sustainable and environmentally responsible urban logistics strategies.

Keywords: Urban logistics, emission, time-dependent routing

1. Introduction

Urban freight transport has become a significant contributor to air pollution and greenhouse gas emissions in cities. Activities related to city logistics, particularly last-mile deliveries, currently account for approximately 25% of emissions from urban transport (Sathaye *et al.*, 2010). The rapid expansion of e-commerce and the increasing demand for immediate delivery services suggest these emissions will sharply rise without targeted interventions. For instance, recent global research indicates that if current trends continue unchecked, carbon emissions from the last-mile delivery traffic in the world's 100 largest cities could increase by more than 30% by 2030 (Bishop, 2021). This trend poses challenges for urban sustainability and has prompted research into strategies to reduce freight-related emissions while maintaining efficient logistics operations.

One strategy focuses on shifting deliveries to the nighttime hours as a promising approach to mitigate the increasing congestion and emissions associated with freight transport (Colberg *et al.*, 2005; Ekström *et al*., 2004). During overnight hours, trucks encounter less traffic and spend less time idling, leading to higher travel speeds and lower per-trip emissions compared to daytime operations (Ekström *et al*., 2004). For instance, a freight simulation study in Belgium found that permitting even limited nighttime deliveries achieved the lowest external costs (including emissions), whereas restricting all freight to daytime hours yielded the highest emissions and social costs (Colberg *et al*., 2005). Similarly, a study for a mid-sized city (Lyon) showed that moving deliveries to off-peak times yields measurable environmental benefits along with significant travel time savings for carriers (Jayol *et al.*, 2022).

These findings suggest that time window regulations can significantly affect freight emissions. Empirical big-data analyses confirm that off-peak travel enables higher average speeds and fewer delays, resulting in lower fuel consumption and emissions per delivery in uncongested conditions (Lu *et al.,* 2018). However, the benefits of off-peak logistics are context-dependent in congested megacities, off-peak periods may still be busy (offering little improvement) (Lu *et al*., 2018), and other external factors must be considered. For example, Mitrovikj and Skácel (2019) found that while moving truck trips out of daytime can reduce peak smog, it also led to higher 24-hour average concentrations of trapped diesel exhaust in some locations. These unintended environmental impacts underscore the need for a balanced approach when instituting off-hour delivery programs, ensuring that gains from reduced congestion are not offset by worsened air quality at sensitive times.

Another strategy of sustainable urban logistics is optimizing the delivery fleet mix and adopting cleaner vehicle technologies. Different studies indicate that various vehicle types, classified by fuel type, vehicle size, and euro standard, generate significantly different amounts of air pollutants and greenhouse gas emissions. For instance, Zheng *et al.* (2020) show that Euro 6 diesel vans emit approximately 91.8% less NO_x compared to Euro 1 diesel vans. Additionally, Euro 5a/b and Euro 6 diesel vans emit about 96.4% less PM than Euro 1 vans. In terms of vehicle size, N1 Class I vans produce approximately 23.8% less NO_x than N1 Class II vans. These comparisons clearly illustrate the substantial reductions in emissions achieved through successive Euro standard advancements, particularly for NO_x and PM, with more pronounced benefits in smaller vehicle classes. Moreover, a comparison of greenhouse gas emissions from different fuel types, considering both Tank-to-Wheel (TTW) and Well-to-Wheel (WTW) perspectives, indicates that diesel vans have the highest overall emissions. Vans powered by compressed natural gas perform moderately better. While electric and hydrogen fuel cell vans produce zero direct (TTW) emissions, their total (WTW) emissions remain substantial due to the energy-intensive processes involved in electricity and hydrogen production. Moreover, replacing conventional diesel trucks with zero-emission or low-emission vehicles substantially reduces tailpipe emissions in urban delivery operations. For instance, battery-electric delivery vans have been shown to virtually eliminate local air pollutants and significantly cut greenhouse gas emissions relative to diesel vans (Sathaye *et al*., 2010). In one comparative study, deploying new electric vans in place of older diesel vans in city logistics resulted in a 93–98% reduction in CO_2 emissions and an 85–99% reduction in regulated air pollutants, assuming a clean electricity supply mix (Sathaye *et al*., 2010). Overall, optimizing which types of vehicles are used is critical to lowering urban freight emissions.

Given these parallel research threads on delivery timing and vehicle type, a logical next step is to consider both dimensions together. There is an emerging recognition that combining off-peak delivery strategies with cleaner vehicle fleets could yield synergistic benefits. Perugu (2019) likewise explore the sustainability of using battery-electric vehicles for off-peak hour deliveries in Stockholm, exemplifying a dual focus on temporal and technological measures. However, our literature review indicates that comprehensive studies integrating both time-of-delivery and vehicle-type comparisons with detailed emissions modelling remain scarce. Prior works tend to examine either the impact of delivery time windows or the impact of vehicle fleet changes in isolation. We found a few studies that explicitly evaluate how different vehicle categories perform under different delivery time scenarios using a high-resolution emission model.

To address this gap, the present study uses the COPERT model to quantify time-dependent emissions from various delivery vehicle types in a real-world urban setting. By inputting the specific vehicle fleet characteristics and driving patterns for Rome's delivery traffic into COPERT, we can estimate emissions of pollutants such as CO, NOx, VOC, PM, and CO_2 for different vehicle classes across different time slots. The goal is to compare emission outcomes across different delivery times and vehicle types. The findings clarify whether off-hour deliveries paired with cleaner vehicles offer cumulative benefits, or if one factor dominates.

The remainder of this paper is organized as follows. Section 2 reviews the relevant literature. Section 3 describes the methodology in detail. Section 4 presents the results, and Section 5 concludes with a discussion and future directions.

2. Literature review

2.1. Temporal and congestion-based variability in urban logistics emissions

The transport sector significantly contributes to environmental degradation, responsible for approximately 25% of global greenhouse gas emissions, with a notable share of these emissions originating specifically from urban logistics operations (Condurat *et al.,* 2017).

Recent literature underscores the critical role of temporal dynamics in urban freight logistics, highlighting the significant impacts of delivery time windows and traffic congestion on urban emissions. Kawsar *et al.* (2024) quantified substantial emissions reductions through off-hour delivery programs, finding that shifting deliveries to nighttime significantly reduced urban freight emissions by approximately 45–67% in cases like New York City and São Paulo, due to improved traffic conditions. However, they also noted that partial off-hour deliveries yielded lower reductions of about 13%, as observed in Bogotá. Their results underline the sensitivity of emission reductions to delivery timing, affirming the environmental benefits achievable through strategic rescheduling of urban deliveries. Research work (Ntziachristos *et al.*, 2009) examined the impact of congestion on CO_2 emissions in urban freight, underscoring that congestion significantly amplifies emissions, particularly during peak periods. Using extensive data from freeway sensors and time-dependent vehicle routing algorithms (Ntziachristos *et al.*, 2009), demonstrate that emission levels are highly sensitive to congestion, vehicle routing constraints, and travel speed variability. The study identifies a nonlinear relationship between travel speeds and emissions. However, emissions substantially increase as speeds decrease due to congestion, especially under real-world stop-and-go traffic conditions. This research emphasizes that the impacts of congestion on emissions are not uniform, and route characteristics significantly influence emission levels, thus stressing the importance of accurately modelling temporal variations in congestion for emission estimation.

In another work (Mądziel, 2023), researcher further extends understanding by quantitatively assessing how regular traffic congestion impacts CO_2 emissions within a distribution network context. Using comprehensive data from online navigation services, this study evaluates the CO_2 emissions of different transport operations, considering factors such as fleet composition, vehicle load, travel speed, and empty running. Mądziel, 2023 shows that regular traffic congestion substantially affects CO_2 emissions due to decreased travel speeds and occasional re-routing decisions, leading to inefficiencies in distribution networks. This study underscores that understanding congestion's impacts on emissions requires detailed and reliable speed data, highlighting online navigation services as valuable tools for future research on logistics emissions.

Research work (Slávik & Gnap, 2019) utilized distance-based emission and static factors for emissions and externalities, not vehicle-technology-specific modelling like COPERT, and quantified the sustainability trade-offs associated with time window constraints in last-mile delivery. While their scoreboard-based method reveals that tighter windows increase emissions and delivery costs, our work extends this analysis by examining how emissions vary across actual time slots, morning, evening, and night, using COPERT model in a real urban context.

Expanding on the impacts of traffic management, Akyol and De Koster (2018) proposed a model predictive control framework integrating COPERT emissions modelling, highlighting the efficacy of variable speed limits in mitigating congestion-induced emissions on urban freeways. Their simulation results demonstrated significant emission reductions with only moderate travel time increases, underlining the importance of dynamic traffic control strategies in urban emission management. Lastly, Mitrovikj and Skácel (2019) highlighted unintended consequences of nighttime freight operations, cautioning that, although off-hour deliveries mitigate congestion during peak periods, they could inadvertently increase pollutant concentrations due to atmospheric stability conditions prevalent at night. This finding stresses the complexity of temporal logistics decisions, suggesting that detailed environmental modelling is necessary when considering temporal adjustments to urban freight logistics. Recent literature highlights various innovative strategies aimed at improving sustainability in urban logistics, particularly focusing on off-peak hour deliveries (OPHD), battery electric vehicles (BEVs), and comprehensive fuel consumption monitoring. Perugu (2019) assessed the combined sustainability impacts of using BEVs for OPHD through a case study in Stockholm. Their study revealed that although BEVs currently incur higher costs than internal combustion engine vehicles for daytime operations, OPHD significantly improves vehicle utilization and travel efficiency, offsetting these costs and offering considerable environmental benefits such as reduced emissions and improved urban accessibility.

Research work (Lu *et al*., 2018) contributed to the urban sustainability discourse by utilizing the COPERT model and real-time GPS data to monitor and analyse fuel consumption in peak and off-peak periods across major urban areas in Pakistan. Their research demonstrated significant efficiency improvements during off-peak periods. Another study (Holguín-Veras *et al.*, 2018) reviewed several international case studies on nighttime urban freight distribution, highlighting significant operational and environmental benefits such as reduced emissions and shorter delivery durations observed in projects like Île-de-France’s off-hour logistics initiative. Specifically, they reported benefits from the Île-de-France project, including reductions in CO_2 emissions (17%), NO_x emissions (22%), particulate matter (PM) emissions (25%), and delivery durations (21%), achieved by shifting deliveries from peak daytime hours to nighttime.

Collectively, these studies reveal significant gaps in current literature regarding detailed emissions modelling explicitly considering vehicle heterogeneity, fuel types, and Euro emission standards under variable congestion conditions and distinct time windows. Addressing this gap, the present research aims to comprehensively integrate COPERT-based emissions modelling with precise temporal and vehicle-specific factors across multiple delivery windows, providing robust and detailed insights into optimizing delivery strategies for minimized urban freight emissions.

2.2. Emission modeling frameworks for urban transport assessment

To effectively assess transport emissions associated with urban logistics, it is essential to adopt a suitable emission model. In recent years, several emission modeling frameworks have been developed, employing diverse methodologies to estimate a wide range of pollutants.

Over the years, emission models have evolved significantly in both complexity and scope, now encompassing a broader range of vehicle categories, fuel types, pollutant classes, and emission processes (Figliozzi, 2011). Early models were limited to estimating a small set of pollutants emitted by warmed-up engines. In contrast, modern models provide comprehensive estimates of both regulated and unregulated exhaust compounds, assess fuel consumption, and integrate real-world driving data under diverse traffic and road conditions. Moreover, while early models relied on data from a limited number of test vehicles, contemporary models are built upon large datasets collected from thousands of vehicles (Figliozzi, 2011). Building on these methodological advancements, several robust and widely recognized emission models have been developed to support accurate estimation of transport-related emissions. Among them, COPERT (Computer Programme to Calculate Emissions from Road Transport) (Kellner, 2016) is extensively applied across Europe. Other prominent frameworks include MOVES (Motor Vehicle Emission Simulator), HBEFA (Handbook of Emission Factors for Road Transport), and EMFAC (EMission FACtors model). These models have been extensively employed in academic and policy-oriented research to evaluate transport emissions, thereby enhancing the accuracy of environmental impact assessments.

The applicability of the COPERT model in various national contexts, including developing countries, has been investigated in multiple studies. For instance, in a study conducted by González-Romero *et al.* (2025), a top-down approach was employed to estimate emissions in Bangladesh, with results benchmarked against World Bank data, demonstrating the model's reliability. In another study (Lu *et al.*, 2018), COPERT was used in conjunction with GPS trajectory data to estimate fuel consumption in three major cities in Pakistan. A case study in Romania (Hammerl *et al.*, 2025) applied COPERT to assess road transport emissions, further illustrating its versatility. Additionally, a Swedish study (Ali *et al.*, 2021) compared COPERT-derived emission factors with on-road remote sensing data. The findings indicated strong agreement for NO_x emissions from passenger cars, moderate alignment for hydrocarbon (HC) emissions from gasoline vehicles, but significant underestimation of NO_x from heavy-duty vehicles and poor agreement for CO estimates. In Rome, Pourkhosro *et al.*, (2025) integrated COPERT Tier-3 at link-level into a Dijkstra-based eco-routing framework to identify routes that balance emission cost and travel time.

The MOVES model has also been extensively utilized in emission research. In Syeda Erum *et al*. (2024), the authors examined the applicability of default MOVES emission rates to Indian conditions. The findings revealed that average emissions of CO, HC, and NO_x in India were 9.54, 8.37, and 9.45 times higher, respectively, than those estimated using the default U.S.-based rates. In another study (Giordano *et al*., 2018), MOVES was applied to analyse urban CO_2 emissions across various road types in Beijing. This research incorporated localized emission factors for passenger cars while retaining the default MOVES values for other vehicle categories.

Several studies have evaluated the accuracy of emission models such as HBEFA and EMFAC by comparing their estimates with real-world measurements. In Mommens *et al.* (2018), HBEFA-based emission estimates were compared with trace gas measurements. The results showed good agreement for total volatile organic compound emissions from light-duty vehicles but revealed that HBEFA overestimated NO_x and CO emissions for the same vehicle category. Similarly, Mousavi *et al*. (2021) assessed HBEFA's NO_x emission estimates using tunnel measurements, finding an overestimation for light vehicles and an underestimation for heavy-duty vehicles. In another study (Savadogo and Beziat, 2021), researchers highlighted uncertainties in HBEFA's greenhouse gas emission estimates for Beijing. The EMFAC model has also been subject to empirical validation. In Bokhorst *et al.* (2017), remote sensing data on NO_x-to-CO ratios were compared with EMFAC outputs, revealing that while CO emissions from gasoline vehicles were accurately captured, NO_x emissions were significantly underestimated. A comparative analysis of various emission models was presented in Figliozzi (2011), highlighting differences in their scope and applicability. The study found that models such as Versit+ and MODEM are limited to passenger cars, while COPERT and HBEFA support a broader spectrum of vehicle categories. Furthermore, COPERT and HBEFA cover a more comprehensive set of pollutants compared to models like PHEM, Versit+, and MODEM. In addition, several traffic-related emission models, such as PHEM, CMEM, and CRUISE, can estimate instantaneous emissions based on detailed vehicle dynamics, including speed, acceleration, and engine parameters. While these models offer high-resolution estimates, they require precise input data and are computationally intensive, limiting their practicality to localized analyses rather than large-scale urban applications (Deloison *et al.*, 2020).

Given its broad pollutant coverage, support for diverse vehicle categories, and extensive use across Europe, the COPERT model is particularly well-suited for the present study.

3. Methodology

A web-based logistics optimization platform, LogicoPlus Dashboard (Moving Projects s.r.l.), was used to perform route planning and emissions analysis in urban freight operations. The platform processes operational data, including client information, delivery orders, and vehicle assignments, and generates optimized delivery plans accounting for order dates, customer locations, and logistical constraints. The platform leverages Vehicle Routing Problem (VRP) algorithms to generate efficient delivery routes, factoring in variables such as vehicle capacity, client locations, time constraints, and traffic conditions. In this study, we analyzed a single delivery plan involving two drivers and two LCVs delivering beverages in the city center of Rome. It is worth mentioning that the platform allows users to define a limit on the number of stops in a delivery plan. However, for the purpose of this study, we assumed no such limitation. To compare different vehicle types, we considered five configurations:

- Light Commercial Vehicle, Diesel, N1-I, Conventional (Vehicle 00);
- Light Commercial Vehicle, Diesel, N1-I, Euro 4, DPF (Vehicle 01);
- Light Commercial Vehicle, Diesel, N1-I, Euro 5, DPF (Vehicle 02);
- Light Commercial Vehicle, Diesel, N1-I, Euro 6 d-temp, DPF+SCR (Vehicle 03);
- Light Commercial Vehicle, Petrol, N1-I, Euro 6 d-temp, GDI (Vehicle 04).

According to Anon (2024), in Rome, approximately 64% of logistics vehicles are pre-Euro or Euro 1, 2, 3, or 4. Therefore, we selected a conventional and a Euro 4 diesel LCV as baselines for comparison with newer models. We computed emissions using the COPERT Tier 3 methodology across different scenarios, considering various times of the day and vehicle types. Finally, we compared the total emission costs associated with each scenario.

3.1. Dataset: Case study in Rome

The dataset used in this study was provided by Sviluppo Horeca s.r.l., a food and beverage distribution company operating primarily in Rome, Italy. The dataset consists of approximately 30,000 delivery records from the year 2023 and includes information organized into three categories:

- Client data: delivery points, and order details.
- Product data: types of goods, weights, and volumes.
- Logistics data: timestamps, vehicle types, and capacities.

This data serves as the input for simulating various delivery scenarios. For consistency, only deliveries originating from a single depot in Rome were considered. Within this subset we analyzed a representative daily plan in which two drivers served 78 deliveries. Using the platform, we generated delivery plans (see Fig 1) across different time slots and vehicle configurations. For each scenario, emissions were calculated to evaluate environmental performance.

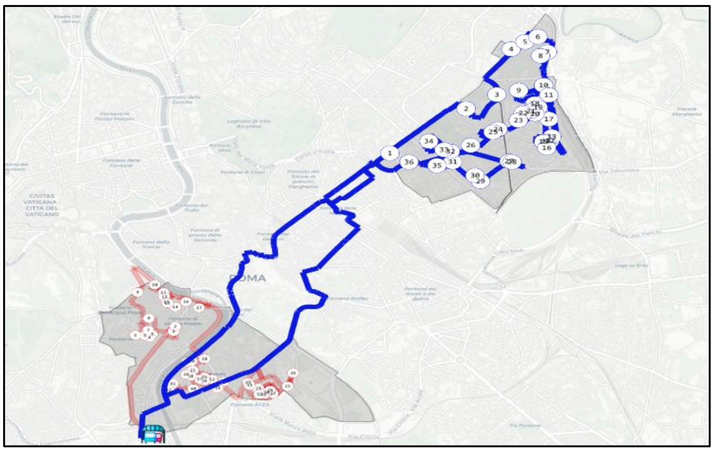

Figure 1. Daily delivery plan with two drivers

3.2. Congestion factor estimations

To ensure emission estimates mirror actual traffic conditions, we calibrated a single congestion factor for each road class and time-of-day interval so that our OSM-based travel-time model reproduces the benchmark behavior of a commercial routing service. The procedure consists of the following steps:

- Time-of-day intervals

We partitioned a weekday into four contiguous slices: morning peak (07:00-09:30), afternoon off-peak (9:30-15:00), evening peak (15:00-19:30), and night off-peak (19:30-07:00). For each interval, we queried the commercial routing API at a representative timestamp. Morning and evening calls captured the highest congestion levels, while afternoon and night calls reflected lighter traffic.

- Benchmark data collection

For a diverse set of origin–destination pairs, we recorded both the geometric polyline and travel time returned by the service in each interval. These "ground-truth" routes served as our target for calibration.

- Congestion factor definition

Let $G = (N, A)$ be the directed graph from OSM, where each arc a has free-flow time t_a^0. We introduced a multiplier γ_g for each road class g so that the effective cost under the interval t becomes:

$$c_a(t) = t_a^0 \times \gamma_{g(a)}(t). \quad (1)$$

- Calibration objective

We followed the two-stage grid-search framework described in Koshy Varghese *et al*. (2024); Salehi *et al*. (2025). After defining objective $J(\gamma)$ that summed, over all calibration trips, the geometric deviation and travel-time error between calibrated and benchmark routes, we performed an exhaustive search over $\gamma_g(t) \in [0.005,5]$ in fixed steps. Because J is nonconvex and small changes in γ_g can alter the shortest-path topology, we evaluated each candidate setting by recomputing all routes and selected the set that minimizes J.

- Resulting factors

The outcome was one congestion multiplier per link class per interval as shown in Table 1. Those multipliers were then hard-wired into our routing engine so that every delivery route used for emission estimation carried travel times that closely match real-world, service-provided estimates, at a tiny fraction of the per-call cost.

Table 1. Calibrated congestion factors γ_g and resulting mean spatial and temporal errors from the benchmark

Scenario	$\gamma_{highway}$	γ_{major}	γ_{road}	Mean △S(m)	Mean △T(min)
Weekday Morning	1.785	2.065	2.345	817.8	6.56
Weekday Afternoon	1.225	1.505	1.785	810.3	3.23
Weekday Evening	1.525	1.925	2.345	759.4	6.88
Weekday Night	0.805	0.945	1.105	723.2	2.30

3.3. Emission computation

Hot Emission Computations

Hot emissions in COPERT Tier 3 are calculated by applying specific emission factors derived from empirical equations related to vehicle speed. Specifically, the hot emission for pollutant i, vehicle technology k, and road type r is computed using the equation:

$$E_{hot;i,k,r} = N_k * M_{k,r} * e_{hot;i,k,r}, \quad (2)$$

where:

- $E_{hot;i,k,r}$: Hot exhaust emissions of pollutant i (in grams), produced in the period concerned by vehicles of technology k driven on roads of type r,
- N_k: Number of vehicles k in operation during the period,
- $M_{k,r}$: Mileage per vehicle (km/veh) driven on roads of type r by vehicles of technology k,
- $e_{hot;i,k,r}$: Emission factor (g/km) for pollutant i, corresponding to vehicle technology k operated on roads of type r.

In order to compute the emission factors, we utilized following equation from the COPERT methodology:

$$EF = \frac{\alpha . V^2 + \beta . V + \gamma + \frac{\delta}{V}}{\varepsilon . V^2 + \zeta . V + \eta} * (1 - RF), \quad (3)$$

where:

- EF: Hot emission factor (g/km),
- V: Speed (km/h),
- α, β, γ, δ, ε, ζ, η: COPERT model parameters specific to vehicle and pollutant types,
- RF: Reduction factor.

To estimate link-level emissions, each road segment in the network was first classified by mapping OSM road types to the COPERT road categories: urban peak, urban off-peak, rural, and highway. Following this classification, emission factors were computed for each segment using the COPERT Tier 3 methodology. The emission factor for a given link was calculated based on the average speed, adjusted by time-of-day-specific congestion factors, as detailed in the previous section. Vehicle-specific parameters were incorporated by selecting the appropriate coefficients (α, β, γ, δ, ε, ζ, η) for LCVs, differentiated by Euro standard, fuel type, and vehicle size. The resulting speed-dependent emission factor (in g/km) was then multiplied by the corresponding segment length to estimate the pollutant emissions per link. Finally, to express the overall environmental impact in a unified metric, all pollutant emissions were monetized using established cost factors from (de Vries, et al., 2024), enabling cross-comparison across time windows and vehicle configurations.

CO_2 Emission Computations (Fuel-based Approach)

The methodology for computing CO_2 emissions strictly follows COPERT Tier 3 principles. It precisely converts speed-specific energy consumption into fuel mass using COPERT-provided calorific values and then computes CO_2 emissions using detailed fuel chemical composition (hydrogen-to-carbon and oxygen-to-carbon ratios). This detailed approach is fully consistent with the Tier 3 methodology as documented in COPERT, ensuring accuracy and reliability of results.

To calculate the mass of CO2 emitted by vehicles in technology k, combusting fuel m, based on the COPERT Tier 3 Model, we used the following equation:

$$E_{CO2,k,m}^{CALC} = 44.011 \times \frac{FC_{k,m}^{CALC}}{12.011 + 1.008 r_{H:C,m} + 16.000 r_{O:C,m}}, \quad (4)$$

where:

- $E_{CO2,k,m}^{CALC}$: mass of CO_2 emitted by vehicle technology *k*, combusting fuel *m*,
- $FC_{k,m}^{CALC}$: fuel consumption by vehicle technology *k*, combusting fuel *m*,
- $r_{H:C,m}$: ratio of hydrogen to carbon atomic for fuel *m*,
- $r_{O:C,m}$: ratio of oxygen to carbon for fuel *m*.

4. Results

The results demonstrate that shifting delivery operations from the morning to the afternoon can lead to a reduction in total emissions and air pollution by approximately 8.71%, as shown in Table 2. However, shifting deliveries from the morning to the evening results in only a negligible change, with no substantial difference observed. Notably, when deliveries are shifted from the morning to the nighttime period, a substantial reduction in emissions, up to 25.57%, can be achieved. This indicates that night-time delivery operations offer the greatest potential for emission mitigation among the tested time slots.

Table 2. Emission cost change (%) by delivery time shift across vehicle types

Vehicle Type	Morning to Afternoon	Morning to Evening	Morning to Night
Vehicle 00	-8.80%	0.24%	-29.58%
Vehicle 01	-8.16%	0.00%	-24.90%
Vehicle 02	-8.66%	0.00%	-23.81%
Vehicle 03	-8.67%	0.00%	-24.00%
Vehicle 04	-9.24%	0.54%	-25.54%
Ave. Percentage	-8.71%	0.16%	-25.57%

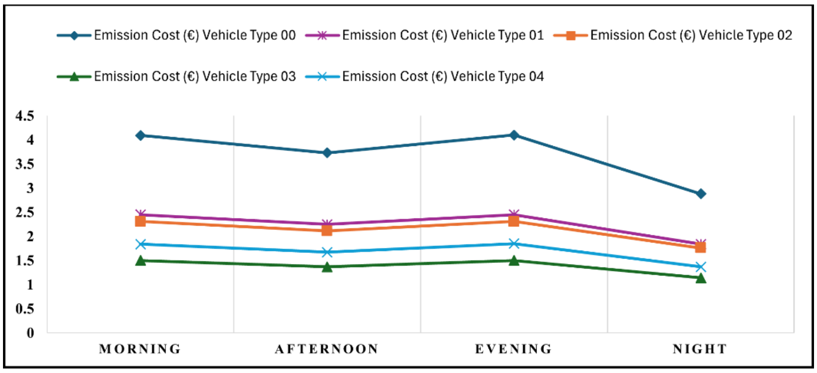

Figure 2. Emission cost (€) of five vehicle types across different times of day

In addition to temporal adjustments, the analysis of vehicle technology and fuel type highlights the importance of fleet composition. As presented in Fig. 2 and Table 3, adopting newer vehicle standards such as Euro 6d-TEMP, equipped with DPF+SCR for diesel engines or GDI for petrol engines, leads to considerable emission reductions compared to conventional fleets. Among all tested configurations, the LCV, Diesel, N1 Class I, Euro 6d-TEMP, DPF+SCR exhibited the lowest emission levels, representing the most environmentally efficient option in the study. This superior performance is illustrated in Fig. 2, where this configuration consistently outperforms other vehicle types across major pollutants.

Table 3. Emission reduction by vehicle type across delivery time relative to baseline vehicle 00

Vehicle Type	Morning	Afternoon	Evening	Night
Vehicle 00	0%	0%	0%	0%
Vehicle 01	40.1%	39.7%	40.2%	36.1%
Vehicle 02	43.5%	43.4%	43.7%	38.9%
Vehicle 03	63.3%	63.3%	63.4%	60.4%
Vehicle 04	55.0%	55.2%	54.9%	52.4%

To better understand the combined effect of time slots and vehicle technologies, a heatmap was created (see Fig. 3), showing the emission cost (€) associated with each combination. The results visually confirm that the lowest emission cost (1.14 €) occurs when using the Euro 6d-TEMP DPF+SCR diesel vehicle (Vehicle 03) during the nighttime. Conversely, the highest emission cost (4.10–4.11 €) is observed for conventional diesel vehicles (Vehicle 00) during morning and evening deliveries. This further supports the finding that both time-based strategies and advanced vehicle technologies are essential for reducing environmental im-pacts in urban logistics.

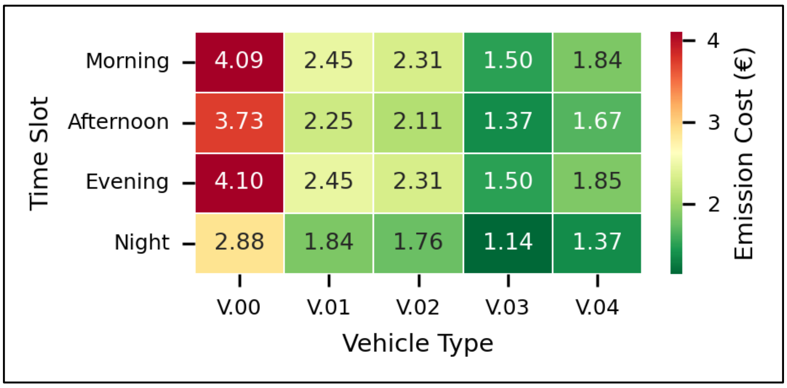

Figure 3. Emission cost heatmap (€) by vehicle type and delivery time slot

5. Conclusion

This paper presented a data driven framework that integrates time dependent vehicle routing with COPERT Tier 3 emission factors to quantify how delivery timing and fleet composition affect urban freight emissions. Applied to operational data from a beverage distributor in Rome, the study compared LCV technologies across four delivery windows, with congestion multipliers calibrated against a commercial routing service to ensure realistic travel times. These results highlight two actionable levers for city logistics: Rescheduling loads from the morning peak to the night off peak reduced monetized emissions by 25.6 %. Renewing the fleet from the baseline diesel van to a Euro 6d TEMP diesel (DPF + SCR) produced a further 63.4 % reduction; the nighttime Euro 6d TEMP scenario achieved the lowest overall cost. While the analysis focused specifically on LCVs, future research should expand to include other vehicle categories used in freight operations. Additionally, this study did not account for the impact of vehicle load, as the COPERT model incorporates load effects only for heavy-duty trucks. Therefore, further investigations are warranted to assess how varying load conditions influence emissions in delivery contexts. The analyses were conducted using the LogicoPlus Dashboard, which served as the simulation and optimization environment for route and emission estimation, supporting data-driven decision-making in sustainable urban logistics.

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- During the preparation of this manuscript the authors used ChatGPT (OpenAI) to improve grammar, spelling, clarity, and paragraph coherence. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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