

Time-Dependent and Energy-Aware Routing in Urban Logistics

Peter Malacký¹

¹ Faculty of Operation and Economics of Transport and Communications, University of Žilina, 01026, Slovakia

Abstract This article examines time-dependent and energy-aware routing in urban logistics as a joint problem of routing, departure-time choice, speed-dependent energy use, and EV charging. It reviews Slovak and international literature, proposes a compact mathematical formulation, compares exact, heuristic, and adaptive solution approaches, and discusses empirical evidence from Slovak and international cases.

Keywords urban logistics, time-dependent vehicle routing, charging planning, congestion modelling

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1. Introduction

The operational problem is to serve urban customers under time windows, traffic congestion, loading constraints, and environmental or energy objectives. In a static VRP, the vehicle state is mostly location, residual capacity, and time. In a time-dependent and energy-aware urban setting, the state expands to include departure-time-dependent travel times, battery state of charge, alternative road paths whose attractiveness changes during the day, charging station choice, charging amount, and possibly station waiting time or charger capacity. This joint state space is the essential reason the problem is difficult in practice and computationally expensive in theory. [1]

Since the city, vehicle class, and fleet size are unspecified, the most defensible scholarly approach is not to hard-code a single urban archetype, but to present a parameterized formulation. In methodological terms, the same structure can model small parcel e-vans, heavier urban delivery trucks, or mixed fleets by changing battery size, charging power, capacity, and fixed vehicle cost; mixed-fleet and heterogeneous-fleet formulations in the literature explicitly support this kind of generalization. [2]

2. Literature Review

Slovak city logistics scholarship is relatively compact and strongly oriented toward governance, transferability of practical measures, and local environmental effects. Gnap and Géc define city logistics as the application of logistics principles to shipment movements in large cities through consolidation gateways, cleaner or more suitable vehicle types, and route optimization, while noting that Slovak practice has re-

lied predominantly on regulatory tools rather than integrated city-logistics systems. That observation remains analytically important because it highlights a gap between formal optimization models and actual institutional implementation in Slovak cities. [3]

A second characteristic of the Slovak literature is its applied focus on urban externalities. Beňová and Gnap's review of night-time urban goods distribution discusses congestion, emissions, and noise together, and shows that off-peak delivery can reduce route duration substantially while creating a parallel need for noise-management measures and local legal compatibility. Petro and Konečný contribute a complementary strand by treating emissions calculation as a managerial and regulatory tool for internalizing transport externalities. The Slovak standards environment has also moved toward formalized emissions reporting, with STN EN ISO 14083 providing a recognized methodological basis for quantifying greenhouse gases from transport-chain operations. [4]

A third useful Slovak contribution is the measurement infrastructure. The Žilina case study by Hrudkay and colleagues describes an urban living laboratory with 26 traffic sensors covering all nine gates of the city centre and publishing 24/7 data on counts, vehicle length classes, and speed. For research on time-dependent routing, that matters because high-frequency local traffic measurements are precisely the type of data needed to calibrate departure-time travel-time functions instead of relying on coarse averages. [5]

2.1. International Literature

International literature is deeper and more formally integrated. In time-dependent routing, a classic step was the use of FIFO-consistent travel-time functions, followed by exact branch-and-price methods for the time-dependent VRPTW and, more recently, road-network formulations that recog-

nize that the best path itself may change with departure time. Recent reviews confirm that time-dependent routing has become a mature field, but also that realism rises sharply when road-network information, multiple paths, and congestion timing are modeled explicitly. [6]

Green and energy-aware routing developed along a related line. Bektaş and Laporte's pollution-routing problem showed that emissions, fuel use, travel time, and routing should be optimized jointly, because pollution depends on speed and load rather than on distance alone. Qian and Eglese extended the logic to time-varying speeds, while Figliozzi's urban freight case-study work showed something analytically non-trivial: it is possible for route distance or duration to increase while total emissions decrease, so "shorter" is not always "greener." [7]

The EV-routing stream added battery feasibility and charging decisions. Seminal contributions include EVRPTW formulations with recharging stations, mixed EV-and-conventional fleets, heterogeneous electric fleets, partial recharge strategies, nonlinear charging functions, time-dependent waiting at charging stations, adaptive routing and recharging policies, and time-dependent EV routing models that optimize speed and departure times together. The current frontier includes exact branch-cut-and-price algorithms for time-dependent EVRP with time windows, charging-station capacity, and even overnight charging scheduling on multi-graphs. [8]

3. Analytical Synthesis

The literature divide is therefore clear. Slovak sources illuminate city access, environmental burdens, night deliveries, and the municipal data and legal structures that shape operations. International sources explain how to optimize the routing-energy-charging system itself. The research gap is not the absence of algorithms, but the lack of city-specific, institutionally implementable digital layers that connect routing models to curb access, loading zones, low-emission rules, charging availability, and public-private data governance. That is precisely the gap now being addressed in EU and OECD policy work on urban logistics, SUMPs, and logistics data sharing. [3]

4. Mathematical Models

A compact integrated formulation can be written on a directed graph $G = (N, A)$ with depot, customers, and charging stations. Let $x_{ijv} = 1$ if vehicle v travels from node i to j , T_i the service start time at node i , b_i the battery state of charge on arrival, and q_i the recharge quantity if node i is a charging station. Following FIFO time-dependent routing, travel time on arc (i, j) depends on the departure time and must preserve chronological order of departures and arrivals. [13]

$$\begin{aligned} & \tau_{ij}(t) \\ = & \text{travel time on } (i, j) \text{ when departing at time } t, \\ & t_1 \leq t_2 \Rightarrow t_1 + \tau_{ij}(t_1) \leq t_2 + \tau_{ij}(t_2). \end{aligned}$$

Time propagation with service times S_i is then

$$T_j \geq T_i + s_i + \tau_{ij}(T_i + s_i) - M(1 - x_{ijv}),$$

with customer time windows $a_i \leq T_i \leq b_i^{\max}$ for all served customers. This is the minimal mechanism that makes route feasibility depend on departure times rather than on static arc lengths.

For energy, a practical approximation used in the green-routing and TDEVRP literature expresses consumption as a function of distance, speed, and carried load. A compact form reported in the time-dependent EV-routing literature is

$$E(d, v, f) = \alpha(\mu + f)d + \beta \frac{d}{v} + \gamma d v^2,$$

where d is distance, v is speed, f is payload, μ is curb weight, and the three terms correspond respectively to a weight module, engine or auxiliary-time module, and speed module. In the cited formulation, low speeds raise the time-related term, high speeds raise the aerodynamic or speed term, and thus energy and total cost are typically convex in speed rather than monotone.

Battery balance and charging decisions can then be written as

$$b_j \leq b_i - e_{ij}(T_i, f_i)x_{ijv} + q_j + M(1 - x_{ijv}), \quad \underline{B} \leq b_i \leq \bar{B}.$$

At a charger k , total stop duration is not just charging time but

$$\theta_k = w_k(T_k) + g_k(q_k),$$

where $w_k(\cdot)$ is a time-dependent waiting or queue function and $g_k(\cdot)$ may be nonlinear or piecewise-linear, depending on charger technology and charging physics. This is where routing and charging become inseparable: even a small energy shortfall can produce a large time penalty if it triggers detour and queue exposure.

A generic objective for urban EV logistics is therefore

$$\min \sum_{(i,j),v} c_{ij}^{\text{travel}}(T_i, f_i)x_{ijv} + \sum_{(i,j),v} e_{ij}(T_i, f_i)x_{ijv} + \sum_{(i,j),v} p_i q_k + \sum_k \omega_k w_k$$

where travel cost, energy cost, charging price, waiting penalty, and lateness penalty are all explicit. For mixed fleets, fixed vehicle-use costs and technology-specific access constraints are added. The key analytical point is that distance minimization is only a special case of this formulation; it is generally not the correct objective in congested, electrified urban delivery.

This compact structure also clarifies why average-speed models are often too weak. Road-network studies show that the best path between two customers can change over the day, not merely the travel time on a fixed path. In parallel, green-routing studies show that energy or emissions are nonlinear in speed and load. Consequently, the route that minimizes distance, the route that minimizes travel time, and the route that minimizes energy can all differ. [9]

Table 1. Comparative view of core model families used in the literature.

| Model family | Congestion representation | Energy and charging representation | Main managerial value | Main limitation |
|--|--|--|---|--|
| TDVRPTW on customer graph | Interval-based or piecewise FIFO travel times between customers | Usually none | Good for departure-time planning under congestion | Often assumes fixed shortest paths and ignores battery feasibility |
| TDVRPTW on road network | Arc-level time functions on the street network; paths can change by departure time | Usually none | Strong realism for urban navigation and access rules | Large network state space |
| Pollution- or green-routing models | Time-varying speeds and speed-sensitive travel cost or emission functions | Fuel or generalized energy cost; often speed/load dependent | Captures why shortest distance is not always lowest energy cost | Usually weaker on explicit EV charging |
| EVRPTW with recharge | Often static or simplified traffic | Battery balance, charging location, recharge amount, sometimes partial or nonlinear recharge | Good for electrification feasibility and route design | Congestion often modeled coarsely |
| Time-dependent EVRP / time-dependent green VRP | Joint departure-time, speed, battery, and charger decisions, sometimes with queues or station capacity | Explicit EV energy, waiting time, charging time, sometimes exact optimization | Best fit for urban e-logistics | Computationally hardest to deploy at scale |

5. Solution Approaches

Exact methods remain indispensable because they tell us what “optimal” means in integrated routing-energy-charging settings. Branch-and-price was central for the classical time-dependent VRPTW, road-network exact methods extended realism further, and recent branch-cut-and-price algorithms solve time-dependent EVRP with time windows and charging decisions. Exact algorithms are particularly useful for strategic design, benchmark generation, pricing studies, and

validating heuristics on small or medium-size instances. Their weakness is well known: once time, speed, charging, and queue states are all explicit, combinatorial growth is severe. Lu and co-authors explicitly report that a commercial exact solver could handle only very small TDEVRP instances, around 15 customers, which illustrates the scaling problem clearly.

Heuristics and matheuristics dominate realistic planning horizons. Tabu search on time-dependent road networks, ALNS for time-dependent green VRP with time windows, IVNS for TDEVRP, and matheuristics for EVRP with realistic energy models all try to preserve the right physics while scaling to practical instances. In operational terms, they are the right middle ground when a fleet planner needs high-quality solutions in minutes rather than exact proofs in hours.

Table 2. Solution approaches and their operational fit

| Approach | Representative methods | Best use case | Main advantage | Main drawback |
|-------------------------------------|--|--|---|---|
| Exact optimization | Branch-and-price, branch-cut-and-price, road-network exact methods | Strategic design, benchmarking, tariff and charging-infrastructure studies | Optimality guarantees and strong lower bounds | Limited scalability under rich time-energy state spaces |
| Matheuristics | Relax-and-fix, decomposition, route enumeration with exact subproblems | Daily planning for medium-size fleets | Strong solution quality with richer realism | Problem-specific modeling effort |
| Metaheuristics | Tabu search, ALNS, IVNS, hybrid local search | Large urban instances and fast replanning | Good speed-quality balance | No optimality certificate |
| Adaptive or rolling-horizon control | Policy-based re-routing, event-triggered re-optimization | Execution under live traffic and queue uncertainty | Operational robustness | Requires dependable data pipelines and threshold design |

Adaptive and real-time methods become necessary once traffic conditions and charger queues evolve during execution. Sweda, Dolinskaya, and Klabjan develop adaptive routing and recharging policies, while urban-freight research and EU logistics-data recommendations point toward rolling-horizon dispatching supported by shared historical and real-time data. The operational logic is not to continuously re-optimize everything, but to re-plan when deviations exceed thresholds in ETA, SoC, or queue forecasts.

The Slovak evidence is especially useful for calibration. In Žilina, a living laboratory around the city centre deployed 26 lane sensors across nine gates and produced continuous traffic data with five-minute granularity. The study reports about 81.5 thousand inhabitants in the city, approximately 54 thousand vehicle entrances to the concerned area on a typical working day, and an average of 43,814 daily entries to the monitored area between September 2021 and April 2022,

with pre-Easter peaks above 64 thousand entries. For routing research, these figures matter less as fixed benchmarks than as proof that city-specific departure-time traffic profiles can be built with inexpensive municipal sensing rather than assumed from generic speed tables. [5]

International off-peak delivery evidence reinforces the same point from another angle. The Stockholm pilot study found that shifting deliveries to off-peak hours improved driving efficiency, delivery reliability, energy efficiency, and service efficiency. Slovak work reviewing Paris and other European cases similarly reports that route duration fell from about 2 hours 3 minutes to about 1 hour 37 minutes in a Paris night-delivery comparison at nearly identical distance, implying that congestion timing alone can unlock large operational benefits even before route resequencing is improved.

The policy caveat is that off-peak benefits are not “free.” Slovak and European discussions of night delivery repeatedly pair efficiency gains with the need to manage acoustic impacts, loading procedures, and neighborhood acceptability. In Slovak legal conditions, noise control remains bounded by national rules on permissible noise, infrasound, and vibration, so off-peak routing must be treated as a coordinated logistics-and-environment intervention rather than a purely algorithmic rescheduling exercise. [10]

The numbers in Table 3 are stylized rather than city-calibrated; they are intended only to show the interaction between congestion, battery feasibility, and charging, using assumptions consistent with speed/load-dependent EV-routing literature.

Table 3. Illustrative numerical example for one urban EV route.

| Metric | Peak dispatch | Off-peak dispatch |
|--------------------------------------|---|-------------------|
| Departure time | 08:00 | 09:30 |
| Route length | 60 km | 60 km |
| Usable energy at departure | 18.0 kWh | 18.0 kWh |
| Assumed average energy intensity | 0.34 kWh/km | 0.26 kWh/km |
| Route energy need | 20.4 kWh | 15.6 kWh |
| Mid-route charging needed | Yes, 2.4 kWh | No |
| Charging penalty assumed | 3 min charging + 15 min detour/queue = 18 min | 0 min |
| Pure driving time | 3 h 45 min | 2 h 30 min |
| Total route time with 40 min service | 4 h 43 min | 3 h 10 min |

The analytical lesson from the example is important. The energy gap between the two scenarios is only 4.8 kWh, but the operational time gap is much larger because a modest battery deficit can force a charging stop whose dominant cost is not the electricity itself but detour, plug-in, and queue time. That mechanism is exactly why time-dependent congestion and charging planning should be solved together rather than in separate modules. This logic also generalizes well across unspecified urban settings: the more congested the city core

and the thinner the public charging network, the stronger the coupling becomes.

7. Implementation Challenges and Recommendations

The first implementation challenge is data architecture. The European Commission’s urban-logistics recommendations note that freight data are crucial for decision making and that both public and private sectors benefit from data sharing, but they also stress barriers of trust, security, cost, and uneven IT capacity. The same document recommends purpose-driven sharing, interoperable tools, and the digitalization of regulations, parking, charging facilities, and urban assets, rather than building isolated local platforms from scratch. For routing practice, that implies that the relevant bottleneck is often not solver quality but missing access to curb, charger, and regulation data in usable digital form.

The second challenge is regulatory fragmentation. OECD work on urban logistics hubs observes that delivery times, vehicle specifications, and access conditions vary heavily by location and that fragmented rules complicate compliance and route optimization; it also argues that restrictions should be made easily accessible online so they can be integrated into navigation systems. Slovak city-logistics writing reached a similar conclusion earlier from a national perspective, arguing that predominantly regulatory practice without harmonized information access weakens operational efficiency. The tension is structural: cities want context-specific policy, while operators want predictability and interoperability.

The third challenge is charging infrastructure and queue uncertainty. Recent EV-routing research shows that charger capacity and time-dependent waiting can change route feasibility, not merely route cost. At the policy level, AFIR is now applicable across the EU and requires Member States to ensure charging infrastructure for heavy-duty vehicles in urban nodes and safe, secure parking areas, while also setting broader coverage and user-information obligations. In Slovakia, public charging infrastructure has expanded from 2,424 publicly accessible charging points in 967 locations at the end of 2024 to 2,818 points in 1,117 locations by July 2025, which is meaningful progress but still implies ongoing deployment pressure if urban commercial fleets electrify at scale. [11]

The fourth challenge is governance integration. The revised TEN-T framework strengthens the role of 431 urban nodes and requires them to adopt Sustainable Urban Mobility Plans and report indicators, while the Commission’s urban-mobility framework explicitly includes zero-emission urban logistics and last-mile deliveries among policy priorities. This is important because freight routing should not be treated as a stand-alone optimization problem; it should be embedded in city planning that also includes congestion, noise, GHG emissions, accessibility, and land use. OECD makes the same point from a governance perspective, emphasizing that authorities should understand freight better,

define sustainability outcomes clearly, and facilitate collaboration while leaving day-to-day logistics management largely to operators

From these constraints, several practical recommendations follow. First, cities should create a freight-specific digital layer inside SUMP or SUDP practice, including curb rules, loading windows, charger status, and vehicle-access regulations, because routing quality cannot exceed the quality of these input data. Second, operators should adopt rolling-horizon dispatch with event triggers based on ETA drift, SoC deviation, and charger-queue anomalies instead of relying on one-shot morning optimization. Third, public charging strategy should prioritize depot and urban-node reliability before treating public fast charging as a universal substitute for planned energy management. Fourth, off-peak delivery should be used selectively in corridors or districts where acoustic compatibility, equipment standards, and local regulation make it socially feasible. Fifth, emissions accounting should be standardized using ISO 14083-compatible methods, preferably with GLEC-aligned implementation, so that routing, procurement, and policy evaluation use a common carbon logic. [12]

7. Conclusions

Time-dependent and energy-aware urban routing is best understood as a joint optimization problem over route sequence, departure time, road path, speed-dependent energy use, and charging decisions. The literature shows that ignoring congestion produces poor ETA estimates, ignoring energy nonlinearity produces poor environmental results, and ignoring charging queues or capacity produces infeasible or brittle EV plans. Slovak research contributes the crucial institutional and measurement perspective—city rules, environmental trade-offs, night-delivery constraints, and local traffic sensing—while international research contributes richer optimization theory and algorithms. The strongest practical architecture for unspecified urban settings is therefore hybrid: exact models for design and validation, advanced heuristics for planning, and rolling-horizon adaptive control for execution.

For scholarly and operational purposes, the main policy implication is equally clear. Urban logistics decarbonization is not just a matter of buying EVs; it requires synchronized changes in municipal data governance, charger deployment, access regulation, quiet-delivery policy, and standardized carbon accounting. Where those layers are absent, even sophisticated routing models remain underimplemented. Where they are present, time-dependent and energy-aware routing becomes a realistic instrument for cleaner, more reliable, and more governable urban freight systems.

REFERENCES

- [1] Dabia, S., Ropke, S., van Woensel, T., & De Kok, T. 2013. "Branch and Price for the Time-Dependent Vehicle Routing Problem with Time Windows." *Transportation Science* 47(3): 380–396. doi:10.1287/trsc.1120.0445.
- [2] J.Gnap, D.Géc, Vybrané aspekty mestskej logistiky, *Logistický monitor*, ISSN: 1336-5851, <https://www.logistickymonitor.sk/images/prispevky/aspekty-mestskej-logistiky.pdf>
- [3] Hrudkay, K., Jaroš, J., Kudela, P., & Valášková, K. 2022. City Logistics in the Centre of the Slovak County Town. Conference paper, CLC 2022, Bojnice, Slovakia.
- [4] Liu, Y., Baldacci, R., Zhou, J., Yu, Y., Zhang, Y., & Sun, W. 2023. "Efficient feasibility checks and an adaptive large neighborhood search algorithm for the time-dependent green vehicle routing problem with time windows." *European Journal of Operational Research* 310(1): 133–155. doi:10.1016/j.ejor.2023.02.028.
- [5] Bektaş, T., & Laporte, G. 2011. "The Pollution-Routing Problem." *Transportation Research Part B* 45(8): 1232–1250. doi:10.1016/j.trb.2011.02.004.
- [6] C.Castañeda, J. P. Orejuela-Cabrera & J.J.Bravo-Bastidas, Refrigerated electric vehicle routing considering time-dependent temperature energy consumption models, Published: 12 April 2025, Volume 349, pages 1817–1854, (2025)
- [7] Ichoua, S., Gendreau, M., & Potvin, J.-Y. 2003. "Vehicle dispatching with time-dependent travel times." *European Journal of Operational Research* 144(2): 379–396.
- [8] Keskin, M., & Çatay, B. 2016. "Partial recharge strategies for the electric vehicle routing problem with time windows." *Transportation Research Part C* 65: 111–127. doi:10.1016/j.trc.2016.01.013.
- [9] Sweda, T. M., Dolinskaya, I. S., & Klabjan, D. 2017. "Adaptive Routing and Recharging Policies for Electric Vehicles." *Transportation Science* 51(4): 1326–1348. doi:10.1287/trsc.2016.0724.
- [10] Lu, J., Chen, Y., Hao, J.-K., & He, R. 2020. "The Time-Dependent Electric Vehicle Routing Problem: Model and Solution." *Expert Systems with Applications* 161: 113593. doi:10.1016/j.eswa.2020.113593
- [11] Yamin, D., Desaulniers, G., & Mendoza, J. E. 2024. "The Electric Vehicle Routing and Overnight Charging Scheduling Problem on a Multigraph." *INFORMS Journal on Computing* 37(4): 808–830. doi:10.1287/ijoc.2023.0404.
- [12] European Commission. 2024. Sustainable urban mobility planning and monitoring. Directorate-General for Mobility and Transport.
- [13] Bektaş, T., Ehmke, J. F., Psaraftis, H. N., & Puchinger, J. 2019. "The role of operational research in green freight transportation." *European Journal of Operational Research* 274(3): 807–823. doi:10.1016/j.ejor.2018.06.001.