IN-VEHICLE TIME DISPARITIES AND METROPOLITAN BUS COMPETITIVENESS: PLANNING AND MANAGEMENT IMPLICATIONS FROM METROPOLIS GZM

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Public transport performance is a central concern in metropolitan management and spatial planning because travel-time competitiveness influences modal split, service attractiveness, and the efficiency of network design. This study examines the comparative in-vehicle time (IVT) and travel distance of metropolitan bus services and private cars in Metropolis GZM (Upper Silesian and Zagłębie Metropolis) in Poland. The analysis covers three datasets: all metropolitan lines (AML), main metropolitan lines (MML), and feeder metropolitan lines (FML). Using timetable-based bus travel data and matched Google Maps car routes for a consistent late-evening weekday comparison, the study evaluates cumulative travel from each line origin to successive stops and then applies a full-sample and reduced-set benchmarking procedure to check whether the main ranking is stable after excluding outlying lines. The results show that buses are substantially less time-competitive than private cars, although the scale of the gap differs by line hierarchy. For AML, the average relative IVT is 237.6%, compared with 177.0% for MML and 247.9% for FML. Average relative distance values are materially lower, at 128.4%, 111.0%, and 133.4%, respectively, indicating that the principal disadvantage is temporal rather than geometric. A descriptively pronounced increase appears beyond the 40th stop in AML and FML, while no comparable jump is observed for MML. Benchmarking by synthetic indicator identifies AP as the strongest overall line, M107 as the strongest feeder line, and M11, M100, and M108 as the most consequential underperformers. The hierarchy-sensitive ordering is preserved in the reduced-set values, supporting the robustness of the central comparative conclusion. The findings support the managerial value of a hierarchical network structure while showing that competitiveness deteriorates as route length increases. Because the evidence is based on a single late-evening observation window and compares timetable and platform-estimated travel times, the conclusions are best interpreted as structurally informative planning benchmarks rather than full-day causal estimates.

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INTRODUCTION

Public transport plays a critical role in metropolitan development because it shapes access to jobs, services, and economic activity while influencing congestion, environmental performance, and the day-to-day functioning of urban systems. The relationship between accessibility and urban structure has long been recognized in planning research, where transport systems are understood as major determinants of land-use opportunity and metropolitan interaction patterns [7]. In contemporary sustainable urbanism, public transport is also central to eco-city development because it supports lower car dependence, reduced environmental burden, and more balanced spatial growth [8]. At the same time, passenger attitudes toward public transport and private cars are shaped not only by service availability but also by comfort, convenience, and perceived competitiveness, which often influence everyday mode choice in ways that extend beyond simple network coverage [2].

A central dimension of that competitiveness is travel time. Travel time valuation studies consistently show that journey duration remains one of the most important determinants of traveler behavior and service attractiveness, both in general appraisal and specifically in the public transport context [1, 12]. Although total door-to-door travel time includes walking, waiting, and transfer penalties, in-vehicle time (IVT) remains the most direct operational basis for comparing public and private transport along the same corridor. Recent work has further shown that disparities between car and transit travel times often exhibit strong spatial and temporal variation across metropolitan systems, reinforcing the importance of corridor-level comparison rather than relying solely on aggregate indicators [9]. Similarly, dynamic accessibility research has demonstrated that travel-time-based evaluations can reveal changes in network performance more effectively than static coverage measures alone [3].

Within metropolitan bus systems, such comparisons are especially important because service provision is rarely uniform. Public transport networks tend to display an internal hierarchy, with some lines serving major regional corridors and others providing connecting or feeder functions within local catchments [11]. From an operational standpoint, this implies different expectations of directness, speed, and service role across line categories. Corridor-based service quality assessment has therefore emphasized the need to evaluate route performance in relation to actual travel conditions rather than nominal network presence alone [13]. In parallel, recent studies in transit network design and optimization suggest that effective metropolitan restructuring should account for differentiated service functions, rather than treating all routes as if they served identical strategic purposes [10].

The present study examines this issue in Metropolis GZM, a special unit of local government in Poland encompassing multiple cities and municipalities in the Upper Silesia and Zagłębie Dąbrowskie region. The institutional and spatial context is particularly suitable for this analysis because the metropolitan system already distinguishes line categories and publishes both network representations and planning-oriented optimization materials that reflect a structured approach to service hierarchy [5, 6]. As the largest metropolitan area in Poland, with a population exceeding 2.2 million, GZM provides a strong empirical setting for evaluating public transport competitiveness at metropolitan scale.

The analysis addresses a planning and management question rather than a purely technical one: how competitive are metropolitan bus lines relative to private cars, how consistently does that relationship differ across the hierarchy of line types, and what does that imply for hierarchy-sensitive transport policy? To answer this question, the study uses timetable-based public transport information and route-based car travel data obtained from operational journey-planning sources [14, 4]. The central objective is to evaluate disparities in IVT and travel distance between metropolitan buses and private cars and to interpret the resulting pattern for metropolitan transport management. More specifically, the study contributes by comparing all, main, and feeder metropolitan lines within a common framework, by using reduced-set values as an internal robustness check, and by translating the empirical pattern into practical implications for route hierarchy, service design, and benchmarking. The study is structured in five parts: Introduction, Methodology and Data, Results, Discussion, Limitations and Conclusions.

METHODOLOGY AND DATA

Study area and data sources

The study focuses on Metropolis GZM, a metropolitan institution responsible for coordinating transport, economic cooperation, spatial planning, environmental protection, and related public functions across the region. Its scale and institutional role make it a suitable case for evaluating transport-system performance in a planning context.

Bus travel time and distance data were obtained from the ZTM Katowice timetable, while the corresponding private-car travel time and distance data were derived from Google Maps. For each cumulative observation, the car comparison used the same origin and destination points as the bus segment and retained the standard route and travel-time estimate displayed for the same late-evening weekday window. The comparison was conducted for late evening on a working day. For public transport, the observed bus trip was the last trip of the day; for private cars, the reference route reflected average traffic conditions for the same time window. This design reduced the influence of severe congestion and random road incidents, allowing the analysis to emphasize structural rather than highly volatile traffic effects. At the same time, because bus values are timetable-based and car values are platform estimates rather than direct field observations, the resulting ratios should be interpreted as structured comparative approximations.

Analytical design

The analysis covers the complete population of metropolitan bus lines included in the metropolitan-line system and uses three datasets:

- **AML** – all metropolitan lines,
- **MML** – main metropolitan lines,
- **FML** – feeder metropolitan lines.

The empirical comparison is based on cumulative travel from the initial stop of each line to each successive stop along the route. Because individual lines serve different numbers of stops, the study evaluates competitiveness progressively, stop by stop, rather than only at final route termini. This design makes it possible to observe whether bus competitiveness changes as the route lengthens.

For each dataset, the study calculates:

1. a stop-level average relative IVT indicator,
2. a stop-level average relative distance indicator,
3. a line-level mean relative IVT indicator,
4. a benchmark-based synthetic indicator for line comparison.

Stop-level averages are computed across all available lines at the same cumulative stop index, which keeps the comparison aligned with route progression rather than terminal-only values. The line-level mean relative IVT indicator is treated as a deterrent variable, so the reference object is defined by the minimum value observed within the relevant dataset. A synthetic indicator (S_i) is then used to compare lines within each dataset by expressing each line relative to the best-performing observed line; lower values therefore indicate stronger competitiveness. In this study, S_i is used as a descriptive benchmarking device rather than as an inferential test statistic. The lines are then grouped into four performance categories using the standard deviation method: very good, good, average, and poor. These categories should be read as comparative performance bands within each subset.

Hierarchical interpretation

Because the study is anchored in a metropolitan hierarchy model, line performance is interpreted against expected functional roles rather than against a single uniform standard. Table 1 presents the hierarchy used to guide the interpretation of results.

Table 1: Hierarchical model of public transport used in the analysis

Line type	**Characteristic**	**Expected IVT relation**
Main metropolitan lines	Lines serving corridors between large cities; high frequency of service; minimized number of stops along the route; high passenger turnover at stops	$IVT(\text{bus}) \approx IVT(\text{car})$
Feeder metropolitan lines	Lines connecting selected stops served by metropolitan lines; one end-stop shared with the main metropolitan line; service at all stops along the route	$IVT(\text{bus}) > IVT(\text{car})$
Ordinary lines	Local connection lines within a city and between a city and its outskirts; frequency depends on location and time of day; service includes many stops along the route	$IVT(\text{bus}) \gg IVT(\text{car})$

The hierarchy model frames line performance as a management and planning issue: main lines are expected to approximate private-car performance more closely than feeder or ordinary lines.

RESULTS

Summary performance across the three datasets

Table 2 reports the core comparative results. The first four rows show the full-sample values, while the next four rows provide a reduced-set sensitivity check after the benchmark outliers are removed. In both views, the data show a consistent and substantial IVT disadvantage for buses relative to private cars across all three datasets. However, the magnitude of that disadvantage varies in a way that aligns with the expected service hierarchy.

Table 2: Summary results for AML, MML, and FML (full sample and reduced-set sensitivity check)

Subset	Indicator	AML (%)	MML (%)	FML (%)
	Average relative IVT	237.6	177.0	247.9
	Average relative distance	128.4	111.0	133.4
	Average synthetic indicator (S_i)	167.4	152.4	141.9
	Standard deviation of S_i	39.3	19.6	36.9
	Average relative IVT	197.2	—	208.7
	Average relative distance	117.1	—	122.8
	Average synthetic indicator (S_i)	127.6	114.8	126.5
	Standard deviation of S_i	28.4	7.9	12.9

[a] The first four rows report full-sample values and the second four rows report the reduced-set sensitivity values obtained after excluding the outlying observations identified in the benchmark analysis. For MML, only the reduced synthetic indicator and its standard deviation are reported.

The key result is that **MML performs substantially better than AML and FML in time terms**. The average relative IVT for MML is 177.0%, meaning that travel on main metropolitan lines takes on average 1.77 times as long as travel by private car. By contrast, FML reaches 247.9%, or roughly 2.48 times car travel time. AML, which aggregates the full metropolitan-line system, stands at 237.6%.

A second important pattern is that **relative distance values are materially lower than relative IVT values in every dataset**. This indicates that the principal disadvantage of buses is not simply that they travel farther, but that they require substantially more time to complete comparable journeys. In operational terms, stop-service intensity, route interruptions, and service structure appear to matter more than pure geometric detour alone. The same ordering is preserved in the reduced-set rows, which strengthens confidence that the hierarchy effect is not driven solely by a small number of extreme lines.

Figure 1 presents these full-sample results graphically.

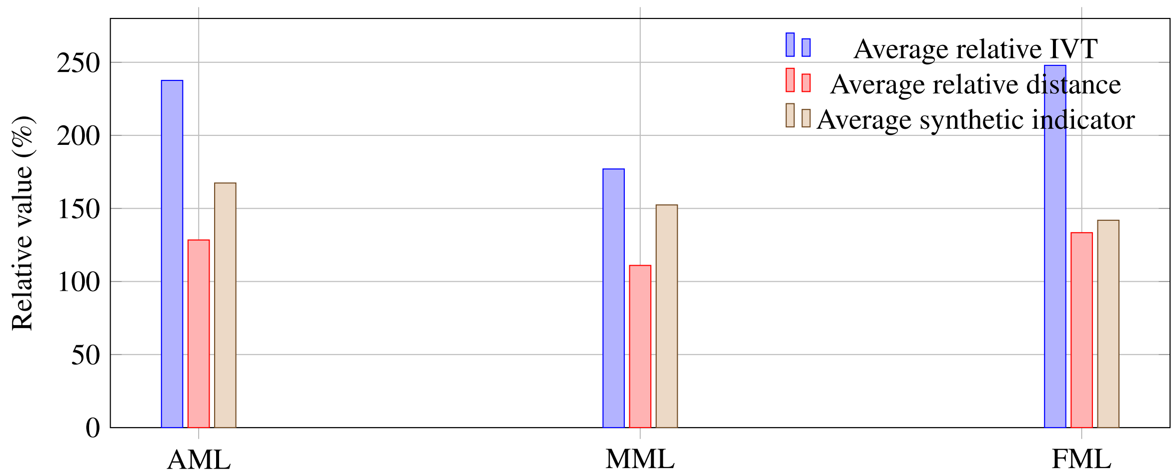

Figure 1: Full-sample comparative indicators for AML, MML, and FML

All metropolitan lines (AML)

For the full metropolitan-line system, public transport achieves an average relative IVT of 237.6%, meaning that bus travel takes, on average, slightly more than twice as long as the equivalent private-car journey. The average relative distance is 128.4%, which is markedly lower than the IVT value and therefore confirms that the time penalty is more severe than the distance penalty.

A descriptively pronounced increase appears after the 40th stop. Up to stops 1–39, the average relative IVT is 197.2%, but for stops 40–44 it rises sharply to 553.0%. A similar pattern is visible for distance, though the shift is smaller: the average relative distance is 117.1% for stops 1–39 and 219.0% for stops 40–44. The magnitude of this change is operationally important, although the present study treats it as a descriptive breakpoint rather than as the outcome of a formal structural-break test. Within that limitation, the pattern indicates that competitiveness declines materially as routes become longer and approach their final sections.

The benchmark analysis identifies AP as the only *very good* line in AML. Its operational role as an airport connection with a limited number of stops makes it the benchmark line for the metropolitan set. Most lines are grouped as *good*, but the differences between the *good* and *average* groups are generally small. Two lines, M100 and M108, are the clearest weak performers. The analysis also notes that some feeder lines perform better than the main metropolitan line M11, indicating that M11 merits closer operational review relative to its formal hierarchical designation.

Main metropolitan lines (MML)

The main metropolitan lines produce the strongest performance in the study. The average relative IVT is 177.0%, and the average relative distance is only 111.0%. In practice, this means that MML comes much closer to private-car performance than either AML or FML.

Unlike AML and FML, **MML shows no comparably sharp descriptive breakpoint**. Although the time penalty still increases with route length, the relationship between stop distance and IVT is weaker and does not display the same abrupt late-route increase. This is a significant operational finding because it implies that the trunk-like part of the metropolitan hierarchy is more stable over route length than the feeder-oriented portion.

The group analysis again identifies AP as the only *very good* line. Seven lines are classified as *good*, eight as *average*, and one line, M11, is classified as *poor*. The average synthetic indicator for the full MML set is 152.4%, with a standard deviation of 19.6%. When the benchmark line AP and the weakest line M11 are excluded, the average synthetic indicator falls to 114.8%, and the standard deviation drops to 7.9%. This reduced-set result functions as a sensitivity check and indicates strong internal homogeneity among the remaining main metropolitan lines.

Feeder metropolitan lines (FML)

Feeder metropolitan lines show the weakest overall competitiveness. Their average relative IVT reaches 247.9%, while the average relative distance is 133.4%. These values confirm that feeder lines impose the largest time penalty relative to private cars.

As in AML, a major descriptive increase is visible at the 40th stop. For stops 1–39, the average relative IVT is 208.7%, but for stops 40–44 it rises to 553.0%. The corresponding distance values are 122.8% and 216.0%. Although the source analysis notes that the relationship between stop distance and IVT is the weakest of the three datasets, the same late-route jump remains operationally important because it shows how extended feeder tails can sharply reduce travel-time competitiveness. As above, this pattern is descriptive and is not presented as a formally tested breakpoint.

Within FML, M107 is the only *very good* line. Eight lines are classified as *good*, one as *average*, and one as *poor*. The average synthetic indicator for the full feeder set is 141.9%, with a standard deviation of 36.9%. After excluding the outlying feeder lines identified in the benchmark analysis, the average synthetic indicator decreases to 126.5%, and the standard deviation falls to 12.9%. This again provides a useful sensitivity check and shows a much more internally consistent reduced feeder set.

DISCUSSION

The results establish a clear managerial and planning pattern: **line hierarchy matters**. The main metropolitan lines, which are intended to serve as the backbone of interurban and interdistrict travel, are markedly more competitive than feeder lines in both time and distance terms. This is consistent with the logic of hierarchical network design, where trunk services are expected to minimize stops and provide relatively direct movement between major nodes, while feeder services accept broader local coverage and, therefore, greater travel-time penalties. The internal robustness checks reported in the summary results reinforce this interpretation, because the relative ordering of MML, AML, and FML is preserved even after the outlying benchmark cases are removed.

At the same time, the findings show that hierarchy alone does not eliminate the competitiveness gap. Even the best-performing main metropolitan set averages 177.0% of car travel time. This means that buses remain slower than private cars even on the strongest part of the metropolitan network. From a management perspective, this suggests that hierarchy is necessary but not sufficient: route directness, stop spacing, service frequency, and transfer integration still require active optimization.

The contrast between IVT and distance is especially important for planning. In all three datasets, the relative IVT values are far worse than the relative distance values. This indicates that the main source of competitive disadvantage is not simply that buses travel farther; rather, the disadvantage is tied more strongly to operational time costs. These time costs arise from stopping patterns, service interruptions, and the cumulative burden of line design. For transport managers, this means that improvement strategies should not focus only on route geometry. Service design interventions that reduce time loss can be just as important as route shortening.

The 40th-stop pattern in AML and FML adds a particularly useful planning signal. In both cases, competitiveness deteriorates sharply after this point in descriptive terms, while no such comparable jump is observed in MML. This suggests that route extension beyond a certain scale can impose disproportionately large time costs in the broader and feeder-oriented parts of the network. For metropolitan service planning, that result supports closer scrutiny of long-tail route sections, especially on feeder lines. It also suggests that very long services may require redesign through restructuring, branching, or stronger transfer-based organization rather than simple route elongation. Because the analysis does not apply a formal breakpoint test, this inference should be read as a strong descriptive indication rather than as a statistically identified threshold.

The line-benchmark findings also carry direct managerial value. AP functions as a benchmark line because its stop structure and strategic corridor role produce the strongest performance. M107 serves a similar benchmarking role within the feeder subset. By contrast, M11 is notable because its weak performance indicates a possible mismatch between its designated role and its observed travel-time profile. This is a critical planning insight: formal categorization should be checked against observed operational performance, while also recognizing that IVT alone is not sufficient to redefine service class. A line designated as part of the metropolitan backbone but performing below feeder comparators should therefore be prioritized for operational review rather than reclassified on the basis of one indicator in isolation.

The broader literature similarly emphasizes that travel time is a decisive factor in perceived public transport quality and modal choice [2, 12]. The present findings are also consistent with city-comparative evidence showing that public transport commonly takes 1.4 to 2.6 times longer than car travel [9]. In that wider context, Metropolis GZM appears broadly comparable to other major metropolitan systems, but the distinction between its main and feeder lines provides a more detailed operational picture than many city-scale averages offer. That said, the present comparison is narrower than a full network-performance audit because it relies on one late-evening observation window and should therefore be interpreted as a structured benchmark rather than as a complete account of day-long operating conditions.

For the management and planning agenda, the implications are clear:

- IVT should be treated as a central performance indicator in network management.
- Main-line design should prioritize directness and stop minimization where demand patterns justify it.
- Feeder services should be evaluated not only for coverage but also for the cumulative time penalties created by long route tails.
- Benchmarking should be used to reassess whether formal line classifications remain operationally justified.

LIMITATIONS AND FUTURE RESEARCH

The study has several limitations that should be considered when interpreting the findings. First, the analysis is based on a specific temporal frame: a working day, during late evening hours, using the last public-transport trip of the day. This choice reduces the influence of extreme congestion and unpredictable incidents, but it also means that the results should not be treated as a full-day performance profile. Peak-hour conditions could produce different absolute IVT values and potentially different relative relations between bus and car travel. Repeated observations across multiple periods would provide a stronger external validation of the hierarchy effects documented here.

Second, the study focuses on the metropolitan core of the transport system, not the entire bus network. As a result, the reported findings reflect the strongest and most strategic part of the system rather than all ordinary lines. The full network would likely display worse relative IVT values than those observed here.

Third, the analysis centers on IVT and route distance. Although those measures are indispensable for operational benchmarking, the full experience of public transport also includes waiting time, transfer coordination, access time, comfort, and crowding. The study explicitly notes that overcrowding in peak periods and waiting for connecting services can further reduce real-world competitiveness. In addition, the observed late-route increases are interpreted descriptively, because the present design does not include a formal breakpoint test.

These limitations point toward several fruitful research directions. Future work should evaluate IVT for the entire bus network, compare results across multiple metropolitan areas, integrate spatial visualization techniques, test the stability of the results across multiple time windows, and examine whether demographic and land-use variables help explain spatial variation in IVT outcomes. For management research, additional value could come from combining quantitative IVT analysis with qualitative service-quality evidence and passenger experience data.

CONCLUSIONS

This study shows that public buses in Metropolis GZM are systematically less time-competitive than private cars, but the degree of disadvantage varies meaningfully by service hierarchy. Main metropolitan lines achieve the best performance and come closest to the intended role of a trunk network, while feeder metropolitan lines perform worse and show sharper deterioration on longer routes. For all metropolitan lines and feeder lines, a strong descriptive increase beyond the 40th stop indicates that competitiveness worsens markedly in the extended sections of the network. No comparable late-route jump is visible in the main metropolitan subset.

A central finding is that the time penalty is substantially larger than the distance penalty. This means that metropolitan bus competitiveness is constrained more by operational time costs than by route geometry alone. Because the same pattern is preserved in both the full-sample and reduced-set values, the result is not easily attributed to a single extreme line. Accordingly, transport policy should treat IVT as a primary management benchmark when designing routes, defining stop patterns, structuring feeder-main integration, and setting service priorities.

From the perspective of management and planning research, the study demonstrates the value of linking performance measurement to network hierarchy. It offers a practical framework for identifying strong benchmark lines, diagnosing weak performers, and aligning service classification with observed operational outcomes. At the same time, the contribution is best understood as a structured and policy-relevant benchmark derived from a controlled observation window, not as a complete causal account of metropolitan travel behavior. In metropolitan transport management, such evidence is still highly useful for designing networks that are both strategically coherent and more competitive in daily use.

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