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Optimizing bus rapid transit performance through route analysis: evidence from Trans Metro Deli Medan

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Abstract

Public transportation systems play a vital role in urban mobility, with Bus Rapid Transit (BRT) emerging as a cost-effective solution for medium-sized cities. This study aims to evaluate the operational performance of Trans Metro Deli BRT system in Medan, Indonesia, and propose optimization strategies for underperforming routes. The research employed a comprehensive data collection approach, combining on-board dynamic surveys and static terminal observations. Performance metrics were analyzed using standardized indicators from the Directorate General of Land Transportation guidelines, while Geographic Information System (GIS) analysis and mathematical demand modeling were utilized for route optimization assessment. The study revealed that while Corridors 1-4 maintained satisfactory performance metrics, Corridor 5 significantly underperformed with load factors of 48% during peak hours and 15% during off-peak hours. Route optimization analysis incorporating major educational institutions showed potential daily ridership of 26,190 passengers for Corridor 5, requiring 19 vehicles for optimal service. These findings demonstrate the importance of route alignment with major activity centers and provide transit planners with evidence-based recommendations for BRT system optimization in developing cities.

Keywords

Public transportation, Bus rapid transit, Trans metro Deli Medan, Operational performance

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Introduction

The global transportation sector is a major contributor to climate change and environmental degradation through carbon emissions, fossil fuel dependency, and air pollution [1]. According to recent studies, transportation activities significantly impact CO2 emissions, with a 10% increase in transportation leading to a 5% rise in emissions [1]. Additionally, rising fossil fuel prices and increasing urbanization have created urgent challenges for sustainable urban transportation systems, particularly in developing nations [2]. These challenges are exacerbated by massive migrations to suburban areas and car dependency patterns that strain existing transportation infrastructure [2].

Recent research demonstrates that implementing sustainable public transportation solutions can significantly reduce environmental impact. For instance, Bus Rapid Transit (BRT) systems in Xiamen City achieved reductions of approximately 25,255 tCO2e per year compared to non-BRT alternatives [3]. In Tehran, converting shared lanes to exclusive BRT lines reduced CO emissions by 9%, PM emissions by 1.13%, NOx emissions by 3.45%, and fuel consumption by 5.3% per kilometer [4]. These findings support BRT's viability as a cost-effective alternative to conventional transit while addressing critical environmental concerns. Studies in developing countries like Vietnam have also shown that BRT implementation can positively impact travel behaviors and encourage greater public transportation usage [5].

In developing countries, BRT offers particular advantages due to its lower capital costs, implementation flexibility, and capacity to serve growing urban populations. Indonesia, like many developing nations, has embraced BRT as a solution to urban mobility challenges. The Trans Metro Deli system in Medan represents one of Indonesia's attempts to implement BRT in a medium-sized city. However, while some corridors demonstrate strong performance, others face operational challenges that limit their effectiveness in achieving environmental and social benefits.

Previous research has established several key factors in BRT performance. Studies in Latin America highlight the importance of dedicated lanes, integration with land use planning, and connection to major activity centers [6]. Analysis of systems in Bogotá and Quito demonstrates that successful BRT implementation requires coordination between transportation planning and urban development [7]. Additionally, research on US systems indicates that BRT performance is significantly influenced by station area characteristics and route alignment with travel demand patterns [8].

However, there remains limited research on BRT optimization in medium-sized cities of developing countries, particularly in the Indonesian context. This study addresses this scientific gap by analyzing the operational performance of Trans Metro Deli and proposing evidence-based optimization strategies. The research specifically examines current operational performance across all corridors, analyzes potential demand, and provides recommendations for BRT system.

Based on a comprehensive review of BRT implementation across developing cities, this study proposes an integrated conceptual framework examining how route optimization through high-activity center integration affects system performance. The framework considers three interconnected dimensions: spatial integration with activity centers (educational institutions, commercial areas, and residential zones), route characteristics (coverage area, accessibility, and population density), and system performance metrics (load factor, travel time, and ridership). We hypothesize that BRT routes optimized to serve educational institutions and commercial centers achieve higher load factors than routes serving residential areas alone [4]; route realignment to high-activity zones increases system ridership while reducing operational costs through improved load distribution [4]; and integration of multiple activity centers along optimized routes leads to more balanced bidirectional passenger flows and improved system efficiency [5].

Method

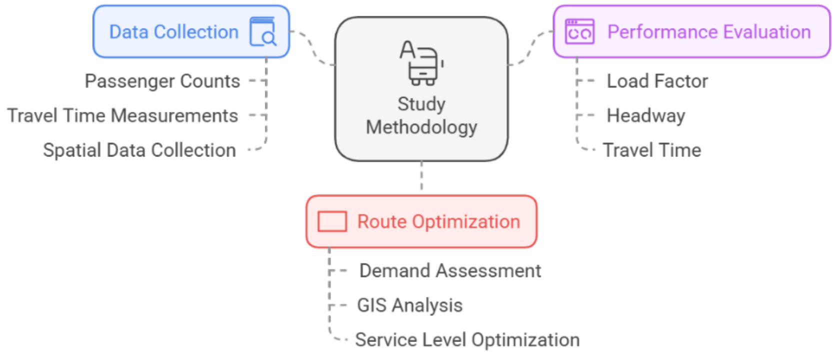

Figure 1. Method

The research methodology follows a comprehensive three-component approach as seen in Figure 1, systematically designed to evaluate and optimize BRT system performance. The data collection phase encompasses systematic passenger counting through on-board surveys during peak (07:00-09:00, 16:00-18:00) and off-peak hours, capturing detailed boarding and alighting patterns at each stop using automatic counting systems [5]. Travel times are precisely measured using GPS-based vehicle tracking, documenting terminal dwell times and intersection delays for service reliability assessment [4]. Spatial data collection utilizes GIS mapping to integrate routes, stations, and major activity centers with land use patterns and population density distributions [2].

Performance evaluation constitutes the second methodological component, focusing on three critical aspects. Load factor analysis assesses vehicle capacity utilization, targeting above 80% during peak hours and maintaining minimum 40% efficiency during off-peak periods. Headway monitoring employs automated systems to track service intervals and frequency variations between peak and off-peak periods. Travel time analysis evaluates segment-wise performance, identifying delay points and analyzing speed profiles across different operational periods. These parameters were selected based on standardized indicators from the Directorate General of Land Transportation guidelines and aligned with established methodological frameworks in transit system evaluation [2], [5].

The route optimization component integrates demand assessment, GIS analysis, and service level optimization. Demand patterns are analyzed through origin-destination matrices and educational institution travel demand modeling [5], while GIS analysis maps population density and activity center accessibility [2]. Service level optimization focuses on vehicle frequency adjustment, stop location rationalization, and route alignment improvements to better serve educational centers, commercial districts, and residential zones [4]. System performance is measured through key indicators including load factor (target >80% during peak hours), schedule adherence (±5 minutes maximum deviation), service regularity (headway deviation <2 minutes), travel time reliability (95% trips within ±10% of scheduled time), passenger wait time (average <10 minutes), and system efficiency measured by operating cost per passenger-kilometer [4].

Results and Discussion

Results

The operational assessment of Trans Metro Deli yielded significant empirical findings across multiple analytical dimensions. This section presents systematic analysis of four critical operational parameters: (1) temporal analysis of passenger volumes, capturing hourly ridership variations and peak-period dynamics; (2) comprehensive service performance metrics, including load factors, operational speeds, and fleet utilization rates; (3) route optimization analysis focusing on Corridor 5's operational enhancement opportunities; and (4) demand distribution patterns analyzing the spatial allocation of potential ridership across educational and residential zones.

Temporal Analysis

A comprehensive temporal analysis of passenger volumes, with reference to Figure 2, reveals intricate patterns and significant variations in ridership across five transport service corridors throughout the operational day. The morning peak at 07:00 showcases strong ridership for Corridors 1-4, ranging from 80-90 passengers, with Corridor 4 leading at approximately 90 passengers, while Corridor 5 dramatically underperforms at only 48 passengers.

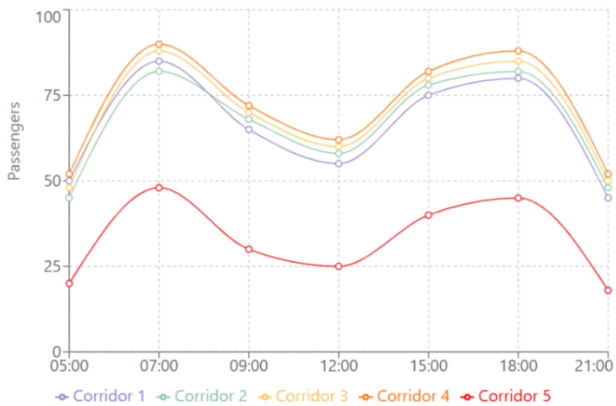

Figure 2. Hourly Passenger Volume

The afternoon/evening peak at 18:00 mirrors this pattern, maintaining high volumes across Corridors 1-4 and Corridor 4 again demonstrating leadership with around 88 passengers, contrasted sharply by Corridor 5's mere 45 passengers. During off-peak midday periods, Corridors 1-4 sustain reasonable occupancy at 55-60 passengers, whereas Corridor 5 plummets to approximately 25 passengers. The service's temporal coverage from 05:00 to late evening consistently highlights the systematic underutilization of Corridor 5 across all time periods. Key insights emphasize the robust performance of Corridors 1-4, with Corridor 4 consistently outperforming others, while Corridor 5 exhibits persistent low ridership. Recommended actions include implementing peak hour capacity enhancements, reviewing Corridor 5's routing and scheduling, developing demand-responsive strategies, and conducting in-depth investigations into the underlying causes of Corridor 5's chronic underperformance. This analysis underscores the critical need for differentiated service strategies that optimize high-performing corridors while addressing the significant challenges faced by Corridor 5.

Service Performance Metrics

A comprehensive operational performance analysis, with reference to Figure 3, reveals nuanced insights across multiple transport service corridors. The study demonstrates significant variations in load factors, with Corridors 1-4 robustly performing at 83-86%, significantly exceeding the 80% standard, while Corridor 5 critically underperforms at a mere 48%.

Metric	Corridor 1	Corridor 2	Corridor 3	Corridor 4	Corridor 5
Load Factor (%)	83	83	84	86	48
Travel Speed (km/h)	13.3	15	26.15	18.75	13.63
Headway (min)	8	8	7	7	8.6
Service Hours	16.14	16.01	16.01	16.15	16
Fleet Utilization (%)	90	90	90	90	90

Figure 3. Performance Metrics Analisis

Travel speed metrics further illustrate the performance disparities, showing corridor speeds ranging from 13.3 to 26.15 km/h, with Corridor 3 excelling at 26.15 km/h and Corridor 5 marginally falling below the 15 km/h standard at 13.63 km/h. The fleet operations present an intriguing challenge, with the current fleet size of 8 buses substantially under the recommended 19-bus standard, despite maintaining an optimal 90% fleet utilization across all corridors. Service hours remain consistently maintained around 16 daily hours, with headway times between 7-8.6 minutes, indicating good temporal accessibility. The systematic analysis unveils critical insights: structural capacity issues, performance disparities, and potential infrastructure inefficiencies, particularly concentrated in Corridor 5. Recommended immediate actions include fleet expansion, targeted service delivery improvements, and route optimizations. Strategic initiatives should focus on developing corridor-specific enhancement plans, reviewing service frequencies, and addressing the identified operational gaps to ensure a more efficient and responsive transportation network.

Demand Distribution

A comprehensive demand distribution analysis reveals significant potential transit demand across the study area, providing crucial insights for route planning and optimization. The analysis identified a total potential daily ridership of 26,190 passengers, with demand sources distinctly split between educational institutions (54.2%) and residential areas (45.8%) with reference to Figure 4.

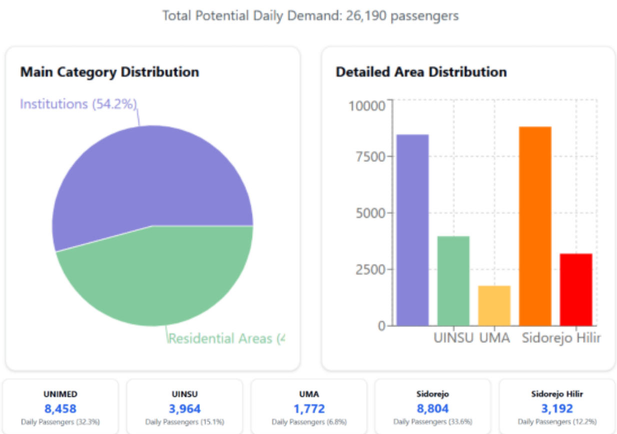

Figure 4. Demand Distribution Analysis

Educational institutions emerge as major demand generators, with UNIMED showing the highest potential at 8,458 daily passengers (32.3%), followed by UINSU with 3,964 passengers (15.1%), and UMA contributing 1,772 passengers (6.8%). The analysis of residential areas reveals substantial demand from Sidorejo with 8,804 potential daily passengers (33.6%) and Sidorejo Hilir adding 3,192 passengers (12.2%).

The concentration of demand in specific nodes, particularly around universities and residential clusters, clearly highlights priority areas that should be considered in route development. The substantial size of the potential user base of 26,190 daily passengers provides strong justification for service enhancement and route optimization efforts. This finding, combined with the detailed understanding of demand distribution, guides the development of effective routing strategies. These insights inform the creation of direct connections between major residential areas and educational institutions, while suggesting the need for carefully planned service frequencies that align with educational institution schedules. Additionally, the analysis supports strategic decisions about stop placement near high-demand points and enables precise capacity planning based on expected peak loads during academic hours. This comprehensive demand distribution analysis thus serves as a foundational element for developing an optimized route structure.

Route Analysis

A comprehensive route optimization analysis for Trans Metro Deli Corridor 5, with reference to Figure 5, reveals transformative potential for enhanced service delivery and increased ridership through strategic modifications. The proposed route design strategically integrates key educational and residential zones, creating a comprehensive coverage area that encompasses 26,190 potential users. By improving access to three major universities - UNSU (3,964 potential users), UMA (1,762 potential users), and UNIMED (8,428 potential users) - the total student coverage reaches 14,194 students.

Figure 5. Trans Metro Deli Corridor 5 Route Optimization Plan

Additionally, the route significantly enhances connectivity to Sidorejo and Sidorejo Hill areas, integrating 11,996 residents into the transit network. The optimization offers multifaceted strategic benefits, including more direct access to educational institutions, improved alignment with urban development patterns, and better last-mile connectivity for communities. The route redesign addresses current operational inefficiencies by creating a more efficient path between key destinations and potentially increasing load factors. Implementation recommendations include a phased route introduction, coordinated communication with educational institutions, and systematic monitoring of emerging ridership patterns.

Supporting measures such as integration with campus transportation plans, strategic bus stop placements, and student-friendly fare systems further strengthen the proposal. By directly targeting the current low-performance issues in Corridor 5, this optimization plan presents a comprehensive approach to dramatically improve service utilization, accessibility, and overall transit network effectiveness, with the potential to transform the corridor from its previous underperformance to a highly efficient and well-integrated transportation solution. The Trans Metro Deli transportation system map provides a comprehensive 1:185,000 scale, north-oriented visualization of Medan's metropolitan mobility infrastructure. Comprising five distinct corridors (K1M in orange, K2M in purple, K3M in pink, K4M in blue, and K5M in yellow), as shown in Figure 6, the map strategically connects key urban areas from Medan Belawan in the north to the southern metropolitan regions.

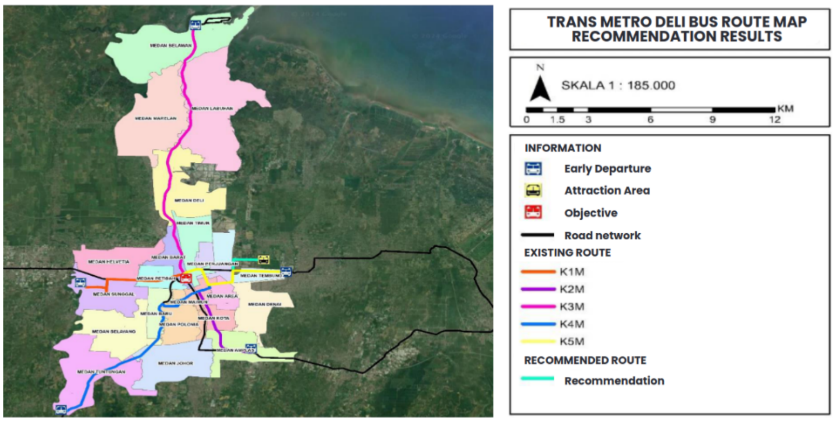

Figure 6. Trans Metro Deli Bus Route Map Recommendation Result

This detailed cartographic representation not only illustrates current transit capabilities but also serves as a blueprint for future infrastructure development, revealing the interconnected nature of urban transportation and demonstrating how carefully planned routes can link different districts, create strategic connections, and enhance overall urban mobility for transportation planners, policymakers, and stakeholders.

Discussion

The operational challenges identified in Corridor 5 align with findings from other BRT studies in developing countries. The low load factors (48%) mirror similar challenges observed in Dar es Salaam's BRT system, where some corridors experienced utilization rates below 50% due to misalignment between routes and key activity centers [9]. However, our identification of substantial untapped demand (26,190 potential users) from educational institutions supports Vergel-Tovar and Rodriguez's [10] findings that BRT success depends heavily on integration with major activity centers, particularly universities and commercial areas.

The importance of educational institutions as key demand generators (54.2% of potential ridership) corresponds with findings from Belo Horizonte's BRT system, where corridors serving university districts achieved higher ridership and user satisfaction compared to primarily residential routes [11]. This supports our route optimization strategy focusing on improving access to three major universities.

Our fleet capacity findings (8 buses versus required 19) echo challenges documented in other developing cities. Matubatuba and De Meyer-Heydenrych [12] found that insufficient fleet size was a major barrier to BRT adoption in emerging markets, particularly affecting service frequency and reliability. The proposed fleet expansion aligns with successful capacity optimization strategies implemented in Bogotá's TransMilenio system [10].

The temporal demand patterns identified, with distinct morning and evening peaks, reflect similar patterns observed in Quito's BRT system. However, our off-peak utilization rates (75-80%) are notably higher than those reported in comparable systems, suggesting potential for sustained ridership with proper route optimization [7].

The proposed route optimization strategy incorporating both educational and residential zones aligns with successful TOD (Transit-Oriented Development) approaches documented by Cervero and Dai [13]. Their research shows that BRT systems integrating multiple activity centers achieve higher ridership and better operational efficiency than single-purpose corridors.

Regarding property value impacts, while our study focused on operational performance, research by Acton et al. [8] suggests that successful BRT corridors can positively influence property values along their routes, particularly when serving major institutional anchors like universities. This potential economic benefit provides additional support for our proposed route optimization strategy.

Our findings on the importance of coordinated implementation echo conclusions from Anas et al. [14], who demonstrated that BRT success in developing cities depends heavily on synchronized planning between transit operations and urban development. This reinforces the need for our proposed multi-dimensional approach to corridor improvement.

Conclusion

This study advances our understanding of BRT system optimization in medium-sized cities of developing countries through a comprehensive analysis of the Trans Metro Deli system in Medan, Indonesia. The research validates our initial hypothesis that BRT routes integrated with high-activity centers achieve superior performance metrics compared to those serving residential areas alone. Through systematic evaluation of operational data and demand patterns, we established that while Corridors 1-4 maintain robust performance with load factors exceeding 80%, Corridor 5's underperformance (48% load factor) stems primarily from suboptimal route alignment rather than lack of demand potential.

Our research makes several significant contributions to the field of sustainable urban transportation. It demonstrates the critical role of educational institutions as demand anchors in developing cities, a finding that extends beyond existing literature focusing primarily on commercial centers. Future research directions should explore the long-term impacts of route optimization on modal shift patterns, particularly among student populations. Additionally, investigating the potential for dynamic service adjustment based on academic calendars could further enhance system efficiency.

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