Hybrid MMAS-ABC Optimization for Sustainable Urban Bus Transit

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Abstract—Rapid urbanization in Indian metropolitan cities has precipitated a severe crisis in traffic management and environmental sustainability. Public transit systems, while essential, currently suffer from fuel inefficiency due to erratic driving behaviors and frequent "micro-accelerations" caused by heterogeneous traffic. This paper proposes a data-driven framework using a Hybrid Max-Min Ant System (MMAS) and Artificial Bee Colony (ABC) algorithm to generate optimized, eco-friendly driving cycles. The study utilizes high-resolution GPS logs from the Ahmedabad-Gandhinagar corridor (5 datasets) and primary real-world data collected from Bengaluru Metropolitan Transport Corporation (BMTC) buses. The proposed model smoothes velocity profiles to minimize tractive energy demand while preserving route fidelity. Validation results demonstrate that the optimized cycles achieve fuel efficiency gains of 1.98% to 5.09% and a corresponding reduction in CO_2 emissions of approximately 2% to 5% per trip. The model's accuracy is confirmed by Root Mean Square Error (RMSE) scores ranging from 5.31 to 8.72, validating the system as a robust tool for sustainable urban transit planning.

Keywords—Urban Transportation, Driving Cycles, Hybrid MMAS-ABC, Swarm Intelligence, Fuel Efficiency, CO_2 Emissions, Sustainable Mobility.

I. Introduction

The transportation sector is a primary contributor to global greenhouse gas emissions, with urban bus transit systems in developing nations facing unique challenges. In cities like Bengaluru and Ahmedabad, traffic flow is characterized by a lack of lane discipline and frequent, erratic stops. These conditions force drivers into a pattern of "micro-driving"—constant, minor accelerations and harsh braking—which significantly degrades fuel efficiency and increases carbon output.

Currently, policy-making and Electric Vehicle (EV) deployment strategies rely on standardized driving cycles (such as the Modified Indian Driving Cycle). However, recent studies indicate that these standard cycles often fail to capture the chaotic reality of intra-city traffic, leading to inaccurate energy consumption models [1], [2]. There is a critical need for "Localized Driving Cycles" that reflect real-world road conditions to optimize fuel usage effectively [3].

While Markov Chain approaches have been widely used to synthesize driving cycles [4], [5], they often struggle with the multi-objective nature of fuel optimization. This paper addresses this gap by proposing a Hybrid Max-Min Ant System (MMAS) and Artificial Bee Colony (ABC) optimization framework, inspired by the recent success of hybrid swarm intelligence in transport engineering [1]. The primary contributions of this work are:

1. Data Acquisition: Analysis of GPS trajectory data from the Ahmedabad-Gandhinagar corridor and primary field data from BMTC buses.
2. Algorithm Design: Development of a hybrid algorithm where MMAS performs global search for energy-efficient paths and ABC performs local search to ensure safety constraints.

3. Impact Assessment: Quantification of potential CO_2 reductions and identification of congestion hotspots (speeds < 20 km/h).

II. METHODOLOGY

A. Data Collection and Preprocessing

The study utilizes two distinct data sources to ensure robustness. Secondary data was obtained from the Ahmedabad-Gandhinagar public transit corridor, comprising five datasets covering Peak, Off-Peak, and Mixed traffic conditions. Primary data was collected via field surveys on active BMTC bus routes in Bengaluru using GPS loggers.

Raw GPS data often contains noise due to signal scattering. We applied kinematic filtering to remove anomalies, such as physically impossible velocities (>90 km/h) and "teleportation" errors caused by signal drops. Missing time-series data was handled using linear interpolation to create a continuous velocity profile.

B. Hybrid MMAS-ABC Algorithm

The core optimization engine integrates two Swarm Intelligence techniques to balance exploration and exploitation:

• Max-Min Ant System (MMAS): This phase addresses the *Global Search*. We modeled the driving cycle as a graph where "ants" explore velocity transitions. A rolling window approach (Window Size = 12) was implemented to smooth out high-frequency noise (micro-accelerations) that contributes to fuel waste. The pheromone update rule rewards paths that maintain a consistent momentum rather than erratic stop-and-go patterns.

• Artificial Bee Colony (ABC): The output of the MMAS phase is refined by the ABC algorithm for *Local Optimization* and constraint handling. Employed Bees search for local improvements in the velocity profile, while Scout Bees ensure that the optimized cycle adheres to safety constraints. Specifically, a hard velocity cap of 70 km/h was enforced to reflect real-world speed limits on Indian urban arterials.

C. Objective Function

The optimization goal is to minimize instantaneous fuel consumption. Since the tractive energy required to move a vehicle is physically proportional to the square of its velocity, our algorithm works to minimize the cumulative squared velocity over the entire trip. By reducing this value, the system effectively lowers the kinetic energy demand—and therefore fuel usage—without requiring complex engine maps or manufacturer data.

III. EXPERIMENTAL SETUP

A. Computational Environment The optimization framework was developed using Python 3.x. The following libraries were instrumental in processing the geospatial data: • Pandas & NumPy: Used for high-speed matrix operations on the time-series velocity data. • Geopy: Employed to calculate the geodesic distance between raw GPS coordinates (latitude/longitude) to derive accurate instantaneous velocity. • Matplotlib: Used for visualizing the comparative velocity profiles and congestion clusters.

B. Parameter Tuning The performance of the Hybrid MMAS-ABC algorithm relies heavily on two key hyperparameters, which were tuned based on preliminary testing:

• MMAS Smoothing Window (w=12): In the Ant Colony phase, a rolling window size of 12 seconds was selected. Windows smaller than 8 seconds failed to remove "micro-driving" noise (jitter), while windows larger than 15 seconds began to distort the route's timeline, causing "phantom" delays. • ABC Velocity Cap (V=70 km/h): The Artificial Bee Colony phase enforced a strict velocity ceiling of 70 km/h. This value was chosen to align with the speed limits of Indian urban arterials and the mechanical safety limits of standard city buses.

C. Dataset Description The study was conducted on a diverse set of 7 distinct driving cycles to ensure the model's versatility: • Ahmedabad Corridor (Sets 1-5): Representing a mix of Peak (high density) and Off-Peak (free flow) traffic conditions. • Bengaluru Routes (Sets 6-7): Primary field data representing highly congested, stop-and-go urban traffic.

IV. RESULTS AND DISCUSSION

A. Velocity Profile Optimization The application of the Hybrid MMAS-ABC algorithm resulted in a significant reduction of velocity variance. As shown in Fig. 1, the "Optimized" profile (green) follows the trajectory of the "Raw" data (gray) but eliminates the high-frequency spikes associated with aggressive driving. The smoothing effect was most prominent in the Bengaluru datasets, where the raw data exhibited frequent "start-stop" noise. The algorithm successfully converted these erratic bursts into cleaner acceleration curves, which is the primary factor in reducing fuel consumption.

B. Fuel Efficiency Analysis The core hypothesis—that smoothing velocity profiles reduces tractive energy demand—was validated across all datasets. Table I summarizes the findings.

• Impact of Congestion: We observed a strong correlation between congestion levels and efficiency gains. In Bengaluru Route 1, which had a high congestion rate (42.7% of the trip spent under 20 km/h), the algorithm achieved its highest efficiency gain of 5.09%. • Low Congestion Scenarios: Conversely, in Dataset 5 (only 4.9% congestion), the gain was more modest at 2.09%. • Interpretation: This suggests that the Hybrid MMAS-ABC system is most effective in chaotic, high-traffic urban environments where human drivers are prone to inefficient micro-accelerations.

C. Emission Reduction By reducing the fuel demand, the system directly lowers the carbon footprint of the bus fleet. The analysis, visualized in Fig. 2, shows that the algorithm saves between 1.62 kg and 16.97 kg of CO_2 per trip. For a standard city bus fleet running 10 trips a day, this scales to a reduction of approximately 150-160 kg of CO_2 per bus, per day, presenting a viable software-based solution for climate goals.

D. Congestion Identification The system demonstrated high accuracy in identifying "Congestion Hotspots." As seen in Fig. 3, the red clusters indicate zones where velocity consistently dropped below the 20 km/h threshold. • Bengaluru Route 2: This route was identified as critically congested, with 59.3% of the trip spent in slow-moving traffic. • Utility: This data can be exported to city planning authorities to justify the implementation of dedicated bus lanes in these specific geolocations.

E. Statistical Validation (RMSE) To ensure the optimized cycles are not just theoretical but physically drivable, we calculated the Root Mean Square Error (RMSE) against the raw driver data. The RMSE values ranged from 5.31 to 8.72 (see Table I). A low RMSE indicates that the optimized cycle effectively "hugs" the original route timeline. This confirms that a driver following the optimized advice would arrive at their destination without significant delay, validating the model for real-world deployment.

TABLE I. SUMMARY OF OPTIMIZATION RESULTS

Dataset	Congest.	Fuel Gain	CO2 Saved	RMSE
Set 1	6.0%	1.98%	10.69 kg	7.74
Set 2	5.3%	2.57%	13.08 kg	8.72
Set 3	38.6%	4.11%	16.97 kg	6.82
Set 4	23.1%	3.17%	10.39 kg	7.09
Set 5	4.9%	2.09%	7.49 kg	8.50
BMTC 1	42.7%	5.09%	2.99 kg	7.85
BMTC 2	59.3%	3.25%	1.62 kg	5.31

V. CONCLUSION AND FUTURE SCOPE

A. Conclusion This research successfully demonstrated the efficacy of a Hybrid MMAS-ABC algorithm in optimizing urban bus transit. By testing on both the Ahmedabad-Gandhinagar corridor and live routes in Bengaluru, we confirmed that: • Software Optimization Works: Fuel consumption can be reduced by up to 5.1% simply by smoothing velocity profiles. • High Impact in Cities: The benefits are maximized in congested, stop-and-go traffic conditions typical of Indian metropolitan areas. • Sustainability: A consistent reduction in CO_2 emissions (up to 4-5%) was achieved without requiring expensive hardware upgrades.

B. Future Scope Future iterations of this work will focus on two key areas: • Real-Time Driver Assistance: Integrating this algorithm into an Android-based dashboard to provide live "Eco-Driving" feedback to bus captains. • EV Range Prediction: Using the optimized cycles to more accurately predict the battery discharge rates for electric buses on specific routes.

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