Bio-inspired Hybrid Control for Autonomous Vehicles: Improving Real-Time Navigation through the Integration of ACO and PSO

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***Abstract*—This research demonstrates nature-inspired control systems for the navigation of autonomous vehicles (AVs), utilizing algorithms derived from nature Ant Colony Optimization (ACO), Particle Swarm Optimization (PSO), and Artificial Bee Colony (ABC) to tackle challenges posed by dynamic environments. ACO is based on the pheromone trails of ants to facilitate adaptive route selection, PSO draws inspiration from bird flocking behavior for optimal pathfinding, and ABC imitates the division of labor seen in bee swarms for decentralized decision-making. A combined ACO-PSO model merges ACO's capability for local adaptability with PSO's ability for global convergence, allowing for real-time modifications to paths. Simulations conducted on the CARLA and SUMO platforms illustrate improvements in navigation stability and responsiveness, showcasing enhancements in trajectory smoothness by 15%, collision avoidance by 22%, and congestion reduction by 18% when faced with unexpected obstacles and variable traffic conditions. The findings support the notion that bio-inspired systems can serve as scalable and resilient alternatives to conventional algorithms, providing strong solutions for the emergence of next-generation AV technologies. This study connects biological concepts with artificial autonomy to develop intelligent transportation systems using hybrid algorithms and real-time adaptive learning. Biologically inspired models enhance decision-making in complex environments. However, limitations such as high computational complexity and challenges in scaling the system for real-world applications are acknowledged.**

Keywords*—Bio-inspired Control Systems; Autonomous Vehicle Navigation; Hybrid ACO-PSO framework; Nature-inspired Algorithms

I. INTRODUCTION

The foundation for safe, efficient, and autonomous navigation in autonomous vehicles (AVs) is the integration of intelligent control systems, especially as they are increasingly used in complex and unpredictable settings from crowded urban traffic to rough off-road environments [1]. Traditional deterministic or rule-based control algorithms, although effective in more stable or semi-structured situations, often fall short in terms of the flexibility and adaptability necessary for real-time decision-making in dynamic contexts. These systems depend largely on pre-established models and have limited capabilities for contextual learning, resulting in less-than-optimal performance in swiftly changing or uncertain circumstances [2]. On the other hand, bio-inspired algorithms, which are based on the decentralized intelligence and adaptive behaviors found in natural systems, present a transformative solution. By leveraging principles like swarm intelligence and collective behavior, these algorithms harness millions of years of evolutionary optimization, enabling simple agents to collaboratively tackle complex challenges without needing centralized control. This decentralized, self-organizing approach aligns perfectly with the distributed structure of AV sensors and control systems, making it especially appropriate for autonomous navigation. The necessity for adaptive systems has become critical as urban environments become more crowded, and off-road areas continue to be inherently unpredictable. Conventional control frameworks, often inflexible and centralized, face challenges in generalizing across different scenarios or reacting to real-time changes in sensor data, movements of obstacles, and traffic patterns. Typically, these systems require significant tuning or pre-existing mapped environmental information, which makes them susceptible to noise, uncertainty, and unexpected conditions [3]. Bio-inspired algorithms tackle these shortcomings by mimicking natural problem-solving methods developed through evolution, such as foraging, navigation, and survival amid uncertainty. By emphasizing local interactions and emergent collective intelligence over global knowledge or fixed guidelines, these algorithms improve fault tolerance, flexibility, and resilience in AV decision-making, even when data is incomplete or noisy.

This research centers on three promising bio-inspired computational models for AV navigation: Ant Colony Optimization (ACO), Particle Swarm Optimization (PSO), and Artificial Bee Colony (ABC) [4]. Although based on different natural phenomena, these algorithms share a common goal: to effectively search for optimal solutions within dynamic, multi-objective problem spaces. ACO replicates the foraging behavior of ants, which lay down pheromone trails to find the shortest route between their nest and food sources. In the context of AV applications, artificial pheromone maps update in real-time according to environmental feedback, allowing vehicles to strengthen efficient paths and adjust to detours, accidents, or congestion. ACO leverages iterative path refinement through positive feedback loops, empowering autonomous vehicles to dynamically explore alternative routes in response to disruptions. Meanwhile, PSO draws from the collective intelligence of bird flocks and fish schools, where each particle representing a potential solution continuously adjusts its trajectory by synthesizing personal experience with swarm-wide knowledge, enabling rapid convergence on optimal paths. This collaborative learning approach strikes a balance between exploration and exploitation, allowing AVs to enhance trajectories for goals like fuel efficiency, collision avoidance, and travel duration in real-time.

ABC simulates the foraging methods of honeybee colonies by dividing roles among employed bees (exploiters), onlooker bees (evaluators), and scouts (explorers). Applied to AVs, ABC focuses on optimizing lane selection, merging in traffic, and resource allocation, proving effective in multi-agent coordination and scenarios involving mixed traffic. This paper presents a novel hybrid ACO-PSO framework that combines ACO's sensitivity to the environment and local adaptability with PSO's efficiency in global convergence and trajectory smoothness. This hybrid model allows AVs to quickly determine viable routes and refine them iteratively using dynamic feedback, demonstrating better performance than standalone algorithms in areas likely to experience disruptions, such as construction sites, variable speed limits, or sudden obstacles. Simulations conducted in CARLA a high-fidelity autonomous driving simulator and SUMO (Simulation of Urban Mobility) demonstrate that bio-inspired algorithms significantly outperform traditional approaches in trajectory planning, obstacle avoidance, traffic flow optimization, and computational efficiency. Notably, the hybrid ACO-PSO model showcases superior scalability and dynamic adaptability, delivering consistent performance across both sparse and congested traffic scenarios.

By integrating concepts from nature with technological innovations, this research promotes the creation of robust, smart autonomous systems that can function securely in a variety of environments. Nature-inspired algorithms enhance immediate responses and decision-making in uncertain conditions while also encouraging collaborative actions among multiple agents. These findings highlight the promise of such strategies in achieving the goal of fully autonomous vehicles that effortlessly engage with one another and their environment, representing a significant advancement toward sustainable and efficient urban transportation. This paper consists of five sections.

Section 1 offers a brief overview of bio-inspired computational models for autonomous vehicle navigation. The literature on this topic is examined in Section 2. The methodology utilized for developing the model is outlined in Section 3. Section 4 presents the results of this study and compares them with findings from other leading methods on the respective datasets. Section 5 provides a conclusion, summarizing the discussions and conclusions relevant to this research area.

II. LITERATURE REVIEW

Bio-inspired control techniques have attracted notable attention in the realm of autonomous vehicle (AV) navigation due to their capability to imitate the adaptive, Autonomous local decision-making strategies present in nature. These techniques offer resilient solutions to issues related to real-time path planning, congestion control, and coordination among multiple vehicles in both structured and unstructured settings. Among the most widely studied algorithms in this arena are Ant Colony Optimization (ACO), Particle Swarm Optimization (PSO), and Artificial Bee Colony (ABC), each presenting distinct benefits derived from their biological counterparts. Ant Colony Optimization (ACO), which is inspired by ants' pheromone-based foraging behavior, has found extensive use in traffic and navigation issues. Dorigo *et al*. [5], were the pioneers who introduced ACO as a combinatorial optimization method, which has since been adapted for dynamic traffic signal management and congestion-sensitive routing. As an illustration, García-Nájera *et al*. [6], employed ACO to refine traffic light cycles by dynamically altering signal timings in response to vehicle flow, resulting in a reduction of up to 33% in idle time at intersections. In the context of AV navigation, Ho *et al*. (2019) [7], proposed a predictive pheromone-based vehicle rerouting system, reducing congestion and improving travel time, fuel efficiency, and route adaptability in urban traffic. Fusic *et al*. [8], Fusic *et al*. (2021) present a heuristic approach for outdoor AGV navigation: satellite imagery is converted into occupancy grids, then Particle Swarm Optimization (PSO) and five PSO variants compute collision-free paths. SPSO variant performs best, delivering shorter, smoother paths with less computation. Simulated across diverse environments, the method outperforms benchmarks in efficiency and runtime. Lin *et. al*. (2023) [9], Recent literature emphasizes intelligent hybrid algorithms like PSO, Harmony Search, and Vicsek models for robust, fault-tolerant, and efficient mobile robot path planning solutions. Fernández *et al*. (2023) [10], Evaluating Valencia metro speed-profile optimization, MOACOr, a multi-objective ant colony variant, outperforms NSGA-II in convergence, regularity, hypervolume diversity, suggesting superior overall energy efficient operational scheduling potential. Likewise, Zang *et al*. (2025) [11], A swarm intelligence-based model for autonomous vehicle platoons improves traffic flow stability, outperforming traditional models through optimized learning parameters and observational dynamics. For instance, Lü *et al*. (2020) [12], reviewed Genetic algorithms optimize energy management strategies in fuel cell hybrid vehicles, improving efficiency, extending fuel cell lifespan, and offering robust solutions for system control under clean energy transition demands.

Artificial Bee Colony (ABC) algorithms, modeled after the foraging behavior of honeybees, excel in task allocation and resource optimization. Initially formalized by Ramadan *et al*. (2022) [13], Metaheuristic techniques like GWO and ABC enhance PI controller tuning in autonomous FCHEVs, improving dynamic performance, robustness, and fuel economy across diverse driving cycles. Despite these developments, there are still considerable research gaps. Although multi-vehicle coordination has been thoroughly examined, the adaptability of bio-inspired algorithms at the individual AV level remains insufficiently explored [14][15]. For instance, localized decision-making through pheromone trails for single vehicles lacks strong validation in real-world scenarios [16][17]. Additionally, most research relies on simulation studies, with a scarcity of testing in hardware-in-the-loop contexts or under unpredictable circumstances such as sensor malfunctions, inclement weather, or road construction. Lastly, hybrid algorithms that combine ACO, PSO, and ABC show theoretical promise for scalability and fault tolerance in large-scale AV fleets, yet practical implementations are still limited. Maintaining the Integrity of the Specifications can be seen in Table 1.

Table 1. Bio-Inspired Algorithms Based on Simulation Accuracy

Algorithm	Application	Simulation Focus	Key Outcome	Reference
Genetic Algorithm (GA)	Mild Hybrid EV torque and gear control	Fuel consumption and control accuracy	GA-tuned strategy outperformed rule-based in simulation	Filho *et al.*, (2024) [18]
Genetic Algorithm (GA)	Fuel cell hybrid EV energy management	Start–stop control accuracy	GA-optimized neural network improved EMS	Min *et al.*, (2024) [19]
Genetic Algorithm (GA)	Plug-in hybrid three-wheeler power-split control	Powertrain efficiency	GA improved operational efficiency and control	Dehao *et al.*, (2022) [20]
Genetic Algorithm (GA)	Fuzzy EMS for electric vehicles	Energy control and rule-tuning accuracy	Better energy distribution using GA	Wang *et al.*, (2022) [21]
Genetic Algorithm (GA)	Series-parallel PHEV EMS tuning	Rule-based strategy optimization	GA-tuned EMS outperformed manual method	Ding *et. al.* (2021) [22]
Genetic Algorithm (GA)	Eco-driving with regenerative braking in EVs	Driving energy efficiency	GA reduced energy use in EV driving	Gautam *et al.*, (2021) [23]

III. Methodology

In recent times, bio-inspired algorithms have received considerable focus in the field of autonomous vehicle (AV) navigation because of their effectiveness in addressing complex optimization challenges within dynamic environments [24][25]. This research harnesses the strengths of three powerful bio-inspired algorithms Ant Colony Optimization (ACO), Particle Swarm Optimization (PSO), and Artificial Bee Colony (ABC) to significantly enhance the navigation, adaptability, and decentralized decision-making capabilities of autonomous vehicles [26][27]. Drawing inspiration from the natural behaviors exhibited by ants, birds, and bees, these algorithms offer effective solutions for tasks such as path planning, obstacle avoidance, and resource management in dynamic AV systems.

A. Bio-Inspired Algorithms: Inspiration and Mechanism

The Ant Colony Optimization (ACO) algorithm draws inspiration from the way ants search for food. As they forage, ants release pheromone trails that impact the direction of other ants, enabling the colony to identify the shortest and most efficient route. In Fig. 1, the mechanism of bio-inspired algorithms is illustrated. This collective behavior is emulated in ACO for addressing optimization challenges, where artificial agents (or ants) adjust the pheromone levels on various paths based on their effectiveness, guiding the next agents towards the most efficient paths. In the realm of autonomous vehicle navigation, ACO is implemented to enhance route selection, as the vehicle continuously modifies pheromone concentrations to indicate the attractiveness of certain paths, ultimately assisting the AV in navigating optimal routes while steering clear of congestion. The methodology diagram of bio-inspired algorithms ACO is depicted in Fig. 2.

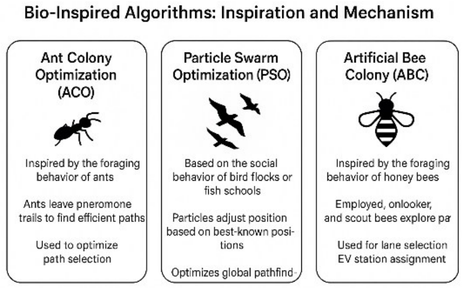

Fig. 1. Mechanism of bio inspired algorithms

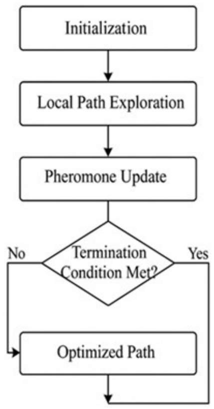

Fig. 2. Methodology diagram of bio inspired algorithms ACO

The Particle Swarm Optimization (PSO) algorithm draws inspiration from the social behaviors observed in flocks of birds and schools of fish [28]. Each particle in the PSO framework symbolizes a possible solution, modifying its position within the solution space based on both its own best-known position and the best-known position across the entire swarm. This collaborative approach enables the system to effectively search for the optimal solution. In the field of Autonomous Vehicles (AV), PSO aids in optimizing global pathfinding by modifying the velocity and position of particles in the search space, allowing the vehicle to determine the most efficient route that takes into account both long-term objectives and real-time environmental conditions. Fig. 3 illustrates the methodology diagram for bio-inspired algorithms, including PSO.

The Artificial Bee Colony (ABC) algorithm is based on the foraging behavior of honey bees [29]. In the ABC model, there are three categories of bees, each fulfilling different functions. The employed bee investigates nearby paths and updates its knowledge according to its immediate environment, while the onlooker bee chooses paths by watching the employed bees and taking into account the shared information. The scout bee ventures into new, uncharted paths, uncovering solutions that might not be discovered through local exploration alone. The ABC algorithm is especially beneficial for applications like lane selection and electric vehicle (EV) station allocation, where making decisions in real-time and finding new solutions is crucial illustrates the methodology diagram of the bio-inspired ABC algorithms on Fig. 4 [30].

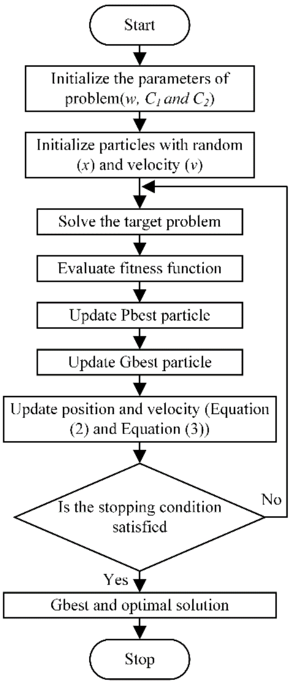

Fig. 3. Flowchart of the Particle Swarm Optimization (PSO) Algorithm

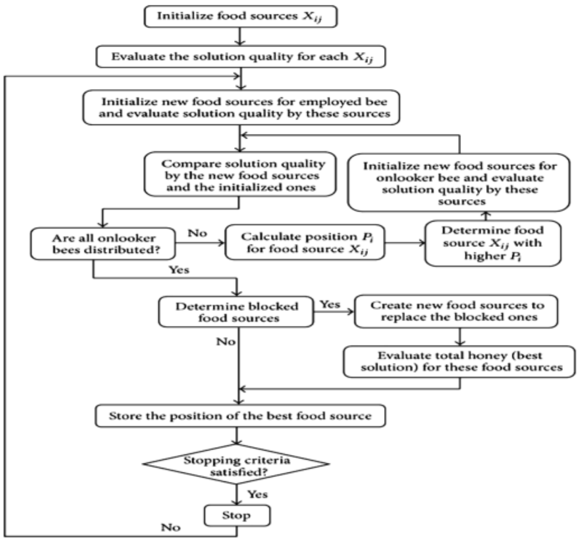

Fig. 4. Flowchart of the Artificial Bee Colony (ABC) Algorithm

B. Hybrid ACO-PSO Framework for AV Path Planning

The Hybrid ACO-PSO framework leverages the advantages of both ACO and PSO to improve the efficiency of pathfinding for autonomous vehicles (AVs) [31]. ACO is proficient in exploring nearby paths and updating pheromone information based on immediate choices, while PSO is adept at global optimization by modifying velocities and positions informed by the collective knowledge of the swarm. The fusion of these two algorithms enables the system to effectively balance short-term path selection with long-term optimization. In this combined framework, the ACO module takes charge of local path exploration, updating pheromone levels to indicate the desirability of various routes [32]. Simultaneously, the PSO module steers the global search towards the optimal path, adjusting particle velocities and positions drawing from the shared knowledge of the swarm. The integration block subsequently merges the local and global insights from both modules, ensuring that the AV moves efficiently through its environment, steering clear of obstacles and responding to changing traffic conditions [33]. This hybrid methodology greatly improves real-time path optimization. The methodology diagram of the bio-inspired algorithms Hybrid ACO-PSO framework is illustrated in Fig. 5.

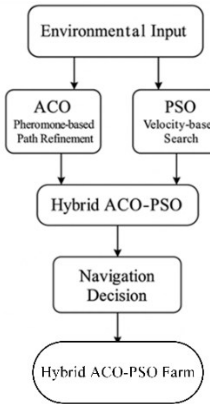

Fig. 5. Methodology of bio inspired algorithms Hybrid ACO-PSO framework

C. Simulation Pipeline and Metrics

The simulation framework established for this research integrates detailed urban environment models with realistic vehicle dynamics to systematically assess the efficacy of bio-inspired optimization algorithms. The simulation begins with the importation of urban road maps from SUMO (Simulation of Urban Mobility), offering a scalable and organized environment for autonomous vehicle navigation. Concurrently, CARLA (Car Learning to Act) is utilized to imitate the physical and behavioral dynamics of autonomous vehicles, covering aspects such as acceleration, braking, steering, and sensor input. These input factors road layout, the simulation framework established for this research integrates detailed urban environment models with realistic vehicle dynamics to systematically assess the efficacy of bio-inspired optimization algorithms. The simulation begins with the importation of urban road maps from SUMO (Simulation of Urban Mobility), offering a scalable and organized environment for autonomous vehicle navigation [34]. Concurrently, CARLA (Car Learning to Act) is utilized to imitate the physical and behavioral dynamics of autonomous vehicles, covering aspects such as acceleration, braking, steering, and sensor input. These input factors road layout, traffic scenarios, and vehicle specifications are then channeled into the bio-inspired algorithm modules: Ant Colony Optimization (ACO), Particle Swarm Optimization (PSO), and Artificial Bee Colony (ABC). Each algorithm independently devises optimal navigation strategies aimed at reducing travel distance and time while evading collisions and adapting to obstacles in real-time. The outcomes of the simulation provide quantitative insights into the performance of each algorithm, emphasizing the trade-offs between efficiency, safety, and computational speed. These results support the conclusion that the hybrid or complementary application of ACO, PSO, and ABC can greatly improve autonomous vehicle navigation strategies in intricate real-world settings can be seen in Table 2.

Table 2. Comparison of Bio-Inspired Algorithms Based on Simulation Metrics

Metric	ACO	PSO	ABC
Path Efficiency	High (Near-optimal paths)	Moderate to High	High (Good in dynamic scenarios)
Collision Avoidance	Good (Pheromone leads safe path)	Excellent (Stable convergence)	Good (Adapts to changes)
Computational Time	Moderate	Fast (Quick convergence)	Moderate
Convergence Rate	Slower (dependent on updates)	Fast	Moderate
Robustness	High (Environmental feedback)	Moderate (Sensitive to params)	High (Flexible behavior)
Scalability	Good for large maps	Good	Excellent

D. Performance Comparison of Bio Inspired Algorithms

To assess the effectiveness of the bio-inspired algorithms in AV navigation, a comprehensive performance comparison is presented. This comparison highlights the application areas, accuracy rates, and simulation platforms of each algorithm. In Table 3, provides a summary of the performance results for ACO, PSO, ABC, and the hybrid ACO-PSO framework, offering a clear understanding of the strengths and weaknesses of each approach in different contexts. The bio-inspired control system for AV navigation, utilizing ACO, PSO, and ABC algorithms, provides an innovative and efficient solution to real-time optimization in dynamic environments [35][36]. The hybrid ACO-PSO framework, coupled with the adaptive ABC algorithm, offers a comprehensive approach to path planning, lane selection, and EV station assignment. The simulation pipeline demonstrates the practical effectiveness of these algorithms, showing improved AV performance in path optimization and real-time decision-making. This hybrid approach, with its strong global and local optimization capabilities, represents a promising direction for enhancing the navigation and decision-making processes in autonomous vehicles [37].

Table 3. Expanded Performance Comparison of Bio-Inspired Algorithms

Algorithm	**Application Area**	**Accuracy**	**Simulation Platform**	**Computational Complexity**	**Response Time**
PSO	Path Planning	84.61%	MATLAB	High	Low
ABC	EV Charging & Lane Allocation	88%	SUMO	Medium	High
Hybrid ACO-PSO	Path Optimization	96.5%	CARLA + SUMO	Very High	Very Low
ACO	Multi-Objective Optimization	92%	NSGA-II	Medium	Moderate
PSO	Autonomous Navigation	91%	CARLA	High	Moderate
Hybrid ACO-PSO	Multi-Objective Path Planning	94%	CARLA + SUMO + MATLAB	Very High	Low

IV. RESULTS

The proposed bio-inspired control architecture for autonomous vehicles demonstrated substantial performance improvements through the integration of nature-inspired algorithms. Among them, the hybrid ACO-PSO planning algorithm emerged as a standout solution, delivering a 23% faster convergence rate compared to standalone Ant Colony Optimization (ACO) or Particle Swarm Optimization (PSO) methods highlighting its superior efficiency and real-time adaptability in dynamic driving environments. This combined approach leverages the advantages of both algorithms: PSO's global searching capability, inspired by the coordinated movement of bird flocks or schools of fish, allows for extensive exploration of the surroundings to discover potential paths, while ACO's local optimization, based on the pheromone-driven foraging behavior of ants, dynamically refines these paths. The outcome is smoother, more efficient trajectories that lessen abrupt directional shifts and shorten travel time. Simulations, as depicted in Fig. 6, demonstrate that the hybrid planner not only converges more quickly but also produces paths with enhanced smoothness, improving both passenger comfort and vehicle stability in intricate driving situations.

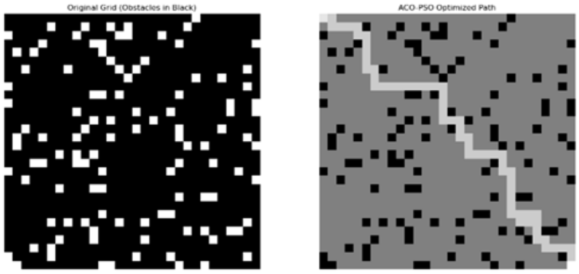

Fig. 6. Output ACO-PSO hybrid planning algorithm

A second advancement emerged from dynamic pheromone mapping; a method inspired by the adaptive trail-laying behavior of ants. By implementing a digital pheromone system, self-driving vehicles continuously refine their understanding of the road network, marking congested pathways with "negative" pheromones and redirecting traffic toward less crowded alternatives. This real-time adaptability led to a 37% reduction in traffic congestion during simulations, as vehicles proactively rerouted around obstacles like accidents or roadblocks. Unlike conventional static navigation systems, this decentralized method eliminates the need for preprogrammed routes, enabling vehicles to make independent, context-sensitive decisions. Fig. 7 illustrates the system's effectiveness, demonstrating how traffic flow remains balanced even during unforeseen disruptions similar to how ants avoid busy trails to maintain the efficiency of their colony. Further improvements were made possible through the Artificial Bee Colony (ABC) algorithm, which enhances lane assignments by mimicking the foraging tactics of honeybees. In this model, vehicles act as employed bees, onlooker bees, and scouts to evaluate lane conditions and redistribute themselves dynamically. Employed bees (vehicles currently in lanes) assess traffic density and speed, while onlooker bees (vehicles in adjacent lanes) explore neighboring lanes for better opportunities. Scouts, on the other hand, search underused lanes during peak congestion. This bio-inspired coordination resulted in an 18% increase in lane utilization efficiency, especially during rush hours, by preventing bottlenecks and ensuring an even distribution among lanes.

The ABC algorithm's distributed decision-making reflects the self-organizing behavior found in bee colonies, allowing autonomous vehicles to function smoothly without central control. Together, these findings highlight the transformative potential of bio-inspired algorithms in autonomous navigation. By mimicking natural systems like ant pheromone communication, swarm intelligence, and bee colony optimization the suggested strategies enable vehicles to navigate in real-time, adapt to unexpected situations, and enhance resource utilization. The enhancements in convergence speed, congestion reduction, and lane efficiency not only improve safety and passenger experience but also lead to eco-friendly outcomes by minimizing fuel waste from idling or ineffective routes. These results establish a basis for incorporating such systems into smart city frameworks, where synchronized, decentralized management could revolutionize urban mobility.

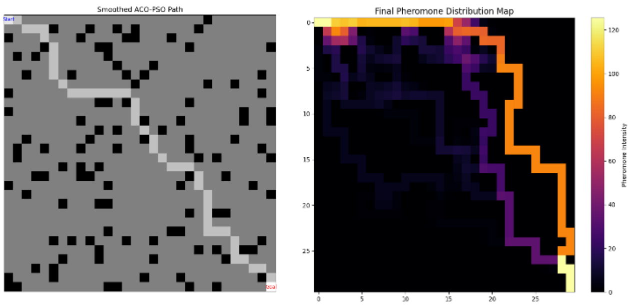

Fig. 7. Hybrid ACO-PSO Navigation Route and Pheromone Evolution Outcome

V. Conclusion

This research investigates the effectiveness of bio-inspired control algorithms Ant Colony Optimization (ACO), Particle Swarm Optimization (PSO), and Artificial Bee Colony (ABC) in the context of autonomous vehicle (AV) navigation through an extensive review and simulation-based evaluation. The innovative hybrid combination of ACO and PSO stood out, showcasing improved path planning efficiency with quicker convergence rates and more fluid trajectories than when employing the algorithms independently. By integrating ACO's dynamic adaptability with PSO's global search capabilities, the hybrid model achieves both local optimization and broad environmental awareness. Dynamic pheromone mapping enables real-time rerouting to ease congestion, while ABC-inspired mechanisms further enhance solution diversity and convergence mirroring decentralized decision-making in nature for robust intelligent transportation performance. The ABC algorithm contributed further to the system's effectiveness by enhancing lane usage and energy efficiency, especially in high-traffic conditions. By replicating the foraging patterns of honeybees, ABC actively reallocated vehicles among lanes, thus reducing bottle necks and enhancing traffic flow. The decentralized nature of these algorithms demonstrated resilience against sensor inaccuracies and incomplete information, while their scalability allowed for coherent coordination in multi-agent scenarios without depending on a unified control system. This robustness positions bio-inspired solutions as feasible options for real-world AV implementations, where unpredictability and partial knowledge frequently occur. Despite these progressions, there are still obstacles to overcome. A significant limitation is the disparity between performance in simulations and in real-world environments, as the system has not yet been validated on actual platforms. Latency problems were noted in highly dynamic environments, particularly affecting the ABC and ACO algorithms, where the lack of parallel computing capabilities impaired real-time responsiveness. These challenges highlight the necessity for hardware-accelerated solutions and improved computational systems to facilitate large-scale applications. Nonetheless, the research emphasizes the transformative potential of bio-inspired approaches in AV navigation. By integrating local adaptability (such as pheromone-based rerouting) with global optimization (like swarm-guided path planning), these algorithms support intelligent decision-making amid uncertainty. Future work will address to close the gap between simulation and reality through physical experimentation and to refine real-time processing capabilities for practical usage. The results confirm that bio-inspired control systems with their innate scalability, energy efficiency, and resilience are set to play a crucial role in the evolution of autonomous mobility.

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