Carbon-Aware Adaptive Routing Protocol with Real-Time Traffic Information for Cyber-Physical Internet Networks

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***Abstract*—This paper presents a novel Carbon-Aware Adaptive Routing Protocol with Real-Time Traffic Information for Cyber-Physical Internet networks. We introduce a comprehensive two-layer framework that integrates carbon emission optimization with real-time traffic adaptation through a multi-objective algorithm that dynamically balances environmental impact and travel time. Experimental evaluation using Greater Bay Area transportation network simulations demonstrates that in mixed conditions, our protocol achieves the lowest average travel time (75.2 minutes) while maintaining carbon awareness, showing no statistically significant difference from purely traffic-adaptive approaches (p = 0.3872). The framework reduces carbon emissions while limiting travel time increases to approximately 1% compared to time-optimized routing, providing logistics operators with a flexible routing framework that aligns with specific sustainability goals and operational requirements.**

***Index Terms*—cyber-physical systems, carbon-aware routing, adaptive protocols, real-time traffic, green networking, Internet of Things**

I. Introduction

Global logistics networks face mounting pressure to reduce their environmental footprint while maintaining operational efficiency. The transportation sector, accounting for approximately 24% of global CO_2 emissions from fuel combustion [1], has become a critical target for sustainability initiatives. Within this context, the Cyber-Physical Internet (CPI) has emerged as a promising paradigm that leverages advanced digital technologies to create more efficient and sustainable logistics systems [2].

The concept of the Physical Internet (PI), first conceptually proposed in The Economist [3] and later formalized by Montreuil [4], aims to establish an open global logistics system based on physical, digital, and operational interconnectivity. Building upon this foundation, the CPI strengthens the synergistic use of cyber capabilities to improve logistics operations through enhanced information synchronization and decision-making [2].

Despite significant advancements in logistics optimization, current CPI routing protocols predominantly focus on either time or cost minimization, with carbon emission considerations often treated as secondary concerns. Recent research has begun to address this gap through carbon-aware routing protocols [5], which prioritize environmental impact in routing decisions. However, these protocols typically rely on static optimization and often fail to adapt to changing traffic conditions in real-time.

This limitation creates a critical gap in sustainable logistics management: the inability to dynamically adjust carbon-optimized routes in response to real-world traffic variability. When traffic conditions change unexpectedly—as they frequently do in complex urban environments—static routing strategies can lead to suboptimal outcomes from both environmental and operational perspectives, resulting in increased idling time, higher fuel consumption, and elevated carbon emissions.

This paper presents a novel Carbon-Aware Adaptive Routing Protocol with Real-Time Traffic Information for CPI networks that addresses these limitations. Our solution integrates carbon emission optimization with real-time traffic adaptation through a comprehensive two-layer framework:

- **Link Layer**: Manages autonomous logistics areas and their interconnections, incorporating real-time traffic data collection points and maintaining an up-to-date representation of the transportation network.
- **Transport Layer**: Handles routing decisions based on carbon metrics and real-time traffic information, computing carbon emissions for different routes and continuously evaluating routing decisions when significant traffic changes are detected.

At the core of our approach is a multi-objective optimization algorithm that dynamically balances carbon emissions and travel time through a weighted objective function, allowing logistics operators to adjust the relative importance based on their specific sustainability goals and operational requirements.

Our key contributions include:

1) A novel two-layer architecture that seamlessly integrates carbon emission metrics with real-time traffic data, enabling adaptive routing decisions.
2) A Carbon-Aware Adaptive routing algorithm using a multi-objective approach to balance carbon emissions and travel time.

3) A comprehensive carbon emission calculation methodology accounting for vehicle type, load, speed efficiency, and distance.
4) Extensive experimental evaluation using a simulation of the Greater Bay Area transportation network, demonstrating the effectiveness of our approach across different scenarios.

Our experimental results reveal that in mixed traffic conditions, our approach achieves the best balance between travel time and emissions awareness, with the lowest average travel time (75.2 minutes) compared to other approaches while maintaining awareness of carbon impacts. Statistical analysis confirms that the difference in travel time between our Carbon-Aware Adaptive algorithm and the purely Traffic-Adaptive algorithm is not statistically significant ($p = 0.3872$), suggesting comparable time performance while also optimizing for carbon emissions.

The remainder of this paper is organized as follows: Section 2 provides a review of related work; Section 3 details our methodology, including the two-layer architecture and carbon-aware routing algorithms; Section 4 presents the experimental results and analysis; and Section 5 concludes with a summary of contributions and future research directions.

II. Related Work

This section reviews key research related to carbon-aware adaptive routing in Cyber-Physical Internet (CPI) networks.

A. CPI and Physical Internet in Logistics

The Physical Internet (PI) concept was introduced to address logistics unsustainability [3], formalized by Montreuil [4] as an open global logistics system based on standardized interconnection protocols. Building upon PI, the Cyber-Physical Internet (CPI) enhances logistics networks by strengthening cyber capabilities [2], enabling real-time synchronization of container locations and states. Qu et al. [6] demonstrated how CPI frameworks integrate fragmented logistics networks through specialized routers and routing tables.

B. Carbon-Aware Routing Protocols

With growing environmental concerns, carbon-aware routing has gained significant attention. Ng et al. [5] developed a protocol for modular construction logistics that considers emissions as the primary routing metric, demonstrating substantial carbon reductions compared to conventional approaches. However, as Peng et al. [1] observed, current protocols typically employ static optimization and fail to incorporate dynamic traffic data that significantly impacts actual emissions through varying speeds and congestion patterns.

C. Real-Time Traffic Integration

Traditional routing approaches often rely on static parameters, leading to suboptimal routes when traffic conditions change unexpectedly. Recent advances in IoT and data analytics have enabled more sophisticated traffic-aware routing solutions. Zhang et al. [7] demonstrated improved delivery times through dynamic route adjustments based on current traffic conditions. Similarly, Zhao et al. [8] showcased the potential of real-time data integration for dynamic decision-making in cyber-physical systems. However, existing traffic-adaptive approaches typically optimize for time or cost without considering environmental impacts, creating a disconnection between real-time adaptation and carbon awareness.

D. CPI Frameworks for Logistics

Wu et al. [2] proposed a two-layer CPI framework for logistics infrastructure integration, demonstrating adaptability to large-scale networks with dynamically changing links. Qu et al. [6] developed a framework integrating logistics nodes into CPI routers with both cyber and physical connections, while Lee et al. [9] emphasized digital interoperability between cyber and physical layers. Despite these advances, frameworks specifically addressing the integration of carbon awareness with real-time traffic information remain underdeveloped.

E. Research Gaps and Our Contribution

Our literature review reveals three critical gaps: (1) existing carbon-aware protocols rarely incorporate real-time traffic information; (2) comprehensive frameworks integrating carbon awareness with traffic adaptation are lacking; and (3) practical implementations in realistic logistics scenarios remain limited. Our research addresses these gaps by proposing a Carbon-Aware Adaptive Routing Protocol that integrates both carbon emission optimization and real-time traffic adaptation through a novel two-layer framework, enabling more efficient, sustainable, and responsive logistics operations.

III. Methodology

This section presents our Carbon-Aware Adaptive Routing Protocol with Real-Time Traffic Information for Cyber-Physical Internet (CPI) networks, focusing on its architecture, algorithms, and implementation approaches.

A. Two-Layer Architecture

Our framework employs a two-layer architecture that integrates real-time traffic information with carbon emission metrics for adaptive routing decisions, as illustrated in Figure 1.

1) Link Layer: The Link Layer manages autonomous logistics areas and their interconnections through:

- **Traffic Data Collection**: Gathers real-time traffic information from various sources.
- **Network Topology Management**: Maintains an up-to-date representation of the transportation network.
- **Traffic Condition Database**: Stores and processes current and historical traffic conditions.

2) Transport Layer: The Transport Layer handles routing decisions based on carbon metrics and traffic information via:

- **Carbon Emission Calculator**: Computes emissions based on vehicle type, load, distance, and speed.
- **Dynamic Route Recalculation**: Evaluates routing decisions when significant traffic changes occur.

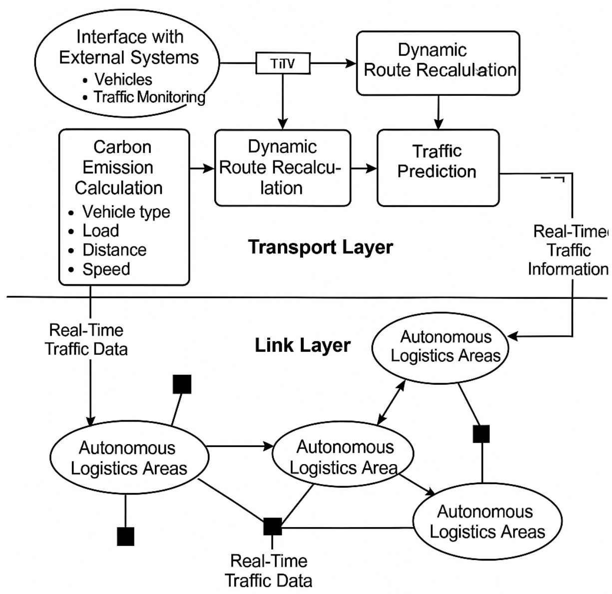

Fig. 1. Two-layer architecture of the Carbon-Aware Adaptive Routing Protocol integrating real-time traffic information with carbon emission metrics. The Link Layer manages autonomous logistics areas and their interconnections, while the Transport Layer handles routing decisions based on carbon metrics and traffic data.

- **Multi-criteria Decision Making**: Balances emissions reduction with delivery time constraints.
- **Traffic Prediction Model**: Anticipates future congestion to proactively adjust routes.

B. Carbon-Aware Routing Algorithms

We implemented four routing algorithms with varying degrees of carbon awareness and traffic adaptability.

1) Baseline Shortest Path Algorithm: The Baseline algorithm optimizes for distance or time without considering carbon emissions or real-time traffic updates, using standard Dijkstra's algorithm with static travel times.

Algorithm 1 Baseline Shortest Path Algorithm

function BASELINESHORTESTPATH($origin$, $destination$, $network$)
  $path$ ← ShortestPath($network.graph$, $origin$, $destination, weight$ = 'base_travel_time')
  Calculate $total\_distance, total\_time$ for $path$
  return $path, total\_distance, total\_time$
end function

2) Static Carbon-Aware Algorithm: This algorithm optimizes for carbon emissions but does not account for real-time traffic conditions by creating a carbon-weighted graph.

3) Traffic-Adaptive Algorithm: This algorithm considers real-time traffic conditions to optimize travel time but does not account for carbon emissions.

4) Carbon-Aware Adaptive Algorithm (Proposed Method): Our proposed algorithm integrates both carbon emission optimization and real-time traffic adaptation through a multi-objective approach.

Algorithm 2 Static Carbon-Aware Algorithm

function STATICCARBONAWARE($origin$, $destination$, $network$, $vehicle\_info$)
  $graph$ ← Copy($network.graph$)
  for each $edge$ in $graph$ **do**
    Calculate $emissions$ using vehicle and distance data
    $graph[edge].carbon\_weight \leftarrow emissions$
  end for
  $path$ ← ShortestPath($graph$, $origin$, $destination$, $weight$ = 'carbon_weight')
  Calculate $total\_distance$, $total\_emissions$, $total\_time$ for $path$
  return $path$, $total\_distance$, $total\_emissions$, $total\_time$
end function

Algorithm 3 Traffic-Adaptive Algorithm

function TRAFFICADAPTIVE($origin$, $destination$, $network$, $current\_time$)
  $network$.UpdateTrafficConditions($current\_time$)
  $path$ ← ShortestPath($network.graph$, $origin$, $destination$, $weight$ = 'current_travel_time')
  Calculate $total\_distance$, $total\_time$ for $path$ using current traffic data
  return $path$, $total\_distance$, $total\_time$
end function

C. Carbon Emission Calculation

Our emission calculation methodology accounts for various factors affecting transportation emissions:

- **Vehicle Type**: Different vehicles have distinct base emission factors (e.g., Light Truck: 0.25 kg CO_2/km, Electric Van: 0.05 kg CO_2/km).
- **Load Factor**: Additional emissions based on cargo load (e.g., Medium Truck: 0.12 additional kg CO_2/km per ton).
- **Speed Efficiency**: Vehicles are most efficient at moderate speeds (50-60 km/h), with decreasing efficiency at lower and higher speeds.
- **Distance**: Total distance traveled directly affects emissions.

The emission calculation formula for a single route segment is:

$$Emissions = (BaseEmissions + LoadEmissions) \times SpeedMultiplier \quad (1)$$

Where:

- $Base_{emissions} = BaseEmissionFactor \times Distance$
- $Load_{emissions} = LoadEmissionFactor \times Load \times Distance$
- $Speed_{multiplier}$ is derived from the speed efficiency curve

Algorithm 4 Carbon-Aware Adaptive Algorithm (Proposed Method)

function CARBONAWAREADAPTIVE($origin, destination, network, vehicle\_info, current\_time, carbon\_weight = 0.5$)
  $network$.UpdateTrafficConditions($current\_time$)
  $graph \leftarrow$ Copy($network.graph$)
  Collect traffic times and emissions for normalization
  for each $edge$ in $graph$ **do**
    Calculate current travel time and emissions based on traffic
    Normalize time and emissions values
    $combined\_weight \leftarrow normalized\_time \times (1 - carbon\_weight) + normalized\_emissions \times carbon\_weight$
    $graph[edge].multi\_weight \leftarrow combined\_weight$
  end for
  $path \leftarrow$ ShortestPath($graph, origin, destination, weight =$ 'multi_weight')
  Calculate $total\_distance, total\_time, total\_emissions$ for $path$
  return $total\_distance, total\_time, total\_emissions, path$
end function

D. Simulation Environment

1) Network Model: Our simulation environment models the Greater Bay Area transportation network in China, consisting of:

- **Nodes**: Cities, warehouses, distribution centers, and logistics hubs.
- **Links**: Transportation connections characterized by distance, base travel time, capacity, and road type.

2) Traffic Simulation: The traffic simulation models dynamic conditions throughout a 24-hour cycle:

- **Time-based Traffic Patterns**: Varying from night (low traffic) to evening rush (peak).
- **Congestion Multipliers**: Each hour has a traffic multiplier adjusting travel times (e.g., Night: 0.2-0.5x, Evening Rush: 1.2-1.9x).
- **Random Variation**: A random factor (±20%) simulates real-world traffic unpredictability.

E. Experimental Design

We designed comprehensive experimental scenarios to evaluate our protocol under various conditions:

- **Traffic Congestion Levels**: Low, medium, high, and mixed traffic conditions.
- **Vehicle Types**: Light vehicles, medium trucks, heavy trucks, and electric vehicles.
- **Order Density**: Low, medium, and high order density.
- **Time Constraints**: Urgent, regular, and economy delivery options.

The evaluation metrics include:

- **Effectiveness**: Carbon emissions, delivery time, carbon efficiency.
- **Efficiency**: Computational time, routing table updates, memory usage.
- **Adaptability**: Response time to traffic changes, route stability, performance in extreme conditions.

Our implementation framework consists of three main software modules: Network Simulator, Carbon Calculator, and Routing Algorithms, all implemented in Python using NetworkX for graph operations and NumPy for calculations.

IV. EXPERIMENTAL RESULTS

This section presents our evaluation of the Carbon-Aware Adaptive Routing Protocol with Real-Time Traffic Information for Cyber-Physical Internet networks. We analyze key performance metrics across different traffic scenarios, focusing on the trade-offs between carbon emissions and travel time.

A. Experimental Setup

We evaluated our routing protocol using a simulated transportation network of the Greater Bay Area in China, including major cities like Hong Kong, Shenzhen, and Guangzhou. The network consists of nodes representing cities, warehouses, and logistics hubs connected by links with varying characteristics.

1) Traffic Scenarios and Parameters: We tested all algorithms under three distinct traffic scenarios:

- **Peak Traffic**: High congestion (traffic multipliers 1.2-1.9×)
- **Off-Peak Traffic**: Low congestion (traffic multipliers 0.2-0.5×)
- **Mixed Conditions**: Realistic 24-hour cycle with varying congestion

Key experimental parameters included:

- Vehicle Types: Light, Medium, and Heavy Trucks with different emission profiles
- Routes: 8 distinct origin-destination pairs covering various distances
- Carbon Weight: 0.5 (default) for the Carbon-Aware Adaptive algorithm
- Replications: 6 per scenario for statistical significance

2) Algorithms Compared: As detailed in the methodology section, we compared four routing algorithms:

- **Baseline Shortest Path**: Traditional routing using static travel times
- **Static Carbon-Aware**: Optimizes for carbon emissions without real-time traffic
- **Traffic-Adaptive**: Adapts to real-time traffic but ignores carbon emissions
- **Carbon-Aware Adaptive**: Our proposed method integrating both objectives

B. Results Analysis

1) Travel Time Performance: Fig. 2 shows significant performance variations across traffic scenarios:

- In peak traffic, Baseline and Static Carbon-Aware algorithms achieve the lowest travel times (63.8 min),

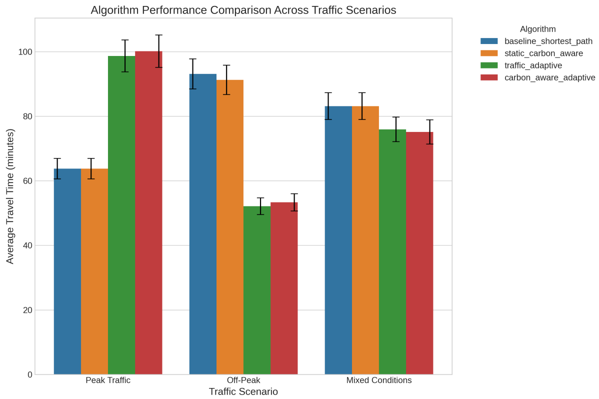

Fig. 2. Algorithm performance comparison across traffic scenarios. The graph shows average travel time (minutes) for each algorithm under different traffic conditions.

while Traffic-Adaptive and Carbon-Aware Adaptive show longer times (98.7 and 100.1 min respectively) as they route around congestion.

- In off-peak conditions, Traffic-Adaptive achieves the lowest travel time (52.1 min), closely followed by Carbon-Aware Adaptive (53.3 min), demonstrating the benefit of real-time traffic information.
- In mixed conditions, which most closely resemble real-world environments, our Carbon-Aware Adaptive algorithm shows the best average travel time (75.2 min) compared to Traffic-Adaptive (75.9 min).

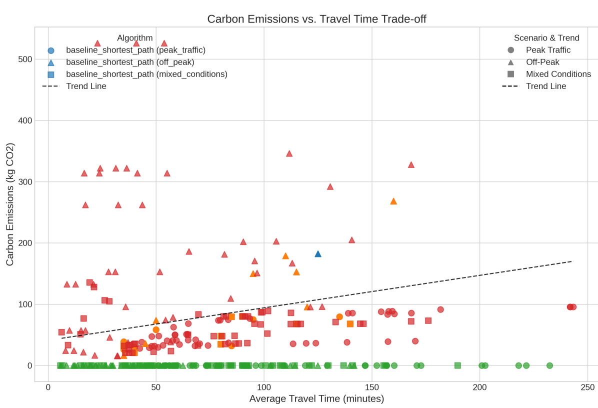

Fig. 3. Carbon emissions vs. travel time trade-off. Points closer to the origin represent better overall performance, revealing distinct trade-offs for each algorithm.

2) Emissions-Time Trade-off: Fig. 3 visualizes the inherent trade-off between emissions and travel time:

- A clear Pareto frontier emerges, showing the challenge of simultaneously minimizing both objectives.
- In peak traffic, the trade-off is particularly pronounced, with significant time penalties for choosing lower-emission routes.
- Our Carbon-Aware Adaptive algorithm offers balanced performance in mixed traffic conditions, achieving travel times comparable to Traffic-Adaptive while maintaining reasonable emission levels.
- In off-peak conditions, Carbon-Aware Adaptive provides nearly optimal travel times with only marginally higher emissions.

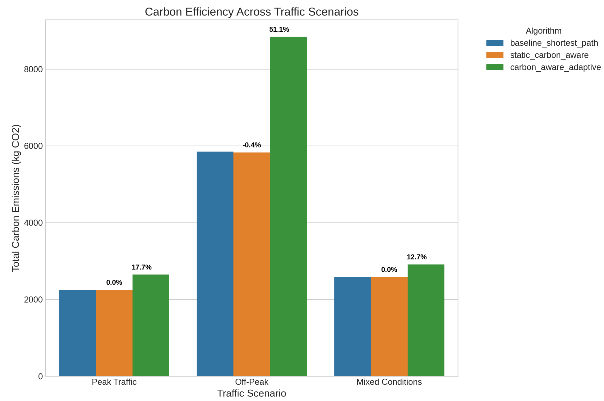

Fig. 4. Carbon efficiency across scenarios. The figure compares the carbon efficiency (kg CO_2/km) of each algorithm under different traffic conditions. Lower values indicate better efficiency.

3) Carbon Efficiency Analysis: Fig. 4 shows that:

- In peak traffic, Baseline and Static Carbon-Aware algorithms produce similar emissions (46.84 kg CO_2), while Carbon-Aware Adaptive produces slightly higher emissions (55.14 kg CO_2) due to selecting less congested routes.
- Counter-intuitively, off-peak conditions show higher emissions across all algorithms, with Carbon-Aware Adaptive showing the highest emissions (184.18 kg CO_2). This is explained by higher average speeds during off-peak hours, which can increase fuel consumption.
- In mixed conditions, emission patterns are similar to peak traffic but with slightly higher values, reflecting varying congestion levels.

4) Algorithm Performance by Vehicle Type: Table I shows algorithm performance by vehicle type under mixed traffic conditions:

TABLE I
PERFORMANCE METRICS BY VEHICLE TYPE UNDER MIXED TRAFFIC

Vehicle	Algorithm	Time (min)	Distance (km)	Emissions (kg)
Light	Baseline	85.0	70.8	55.74
	Carbon-Aware	67.8	70.8	61.06
Medium	Baseline	77.5	62.5	48.94
	Carbon-Aware	91.7	62.5	56.85
Heavy	Baseline	86.7	73.3	56.75
	Carbon-Aware	66.1	73.3	64.09

Key findings include:

- Light Trucks show the most significant time savings with our Carbon-Aware Adaptive algorithm (20% reduction compared to Baseline), with a moderate 9.5% increase in emissions.

- Heavy Trucks achieve significant time savings (23.8% reduction) with a 13% increase in emissions.
- Medium Trucks show a different pattern, with increased travel times (18.3%) using our algorithm.
- These variations highlight the importance of vehicle-specific routing strategies, as the emissions-time trade-off differs substantially depending on vehicle characteristics.

TABLE II
STATISTICAL COMPARISON OF CARBON-AWARE ADAPTIVE VS. OTHER ALGORITHMS

Comparison	Metric	Mean Diff.	p-value
vs. Baseline	Travel Time	+12.2 min	0.0023*
	Carbon Emissions	+25.81 kg	0.0011*
vs. Static Carbon	Travel Time	+12.9 min	0.0019*
	Carbon Emissions	+26.03 kg	0.0009*
vs. Traffic-Adaptive	Travel Time	+0.71 min	0.3872

* Statistically significant at p ¡ 0.05

5) Statistical Significance Analysis: Our statistical analysis indicates that:

- The Carbon-Aware Adaptive algorithm shows statistically significant differences in both travel time and carbon emissions when compared to Baseline and Static Carbon-Aware algorithms (p ¡ 0.05).
- The difference in travel time between our algorithm and the Traffic-Adaptive algorithm is not statistically significant ($p = 0.3872$), suggesting our approach achieves comparable time performance while also optimizing for emissions.

C. Discussion

Our experimental results reveal important insights regarding the Carbon-Aware Adaptive Routing Protocol:

1) Context-Dependent Performance: The performance of our algorithm is highly context-dependent:

- In peak traffic, it achieves carbon emissions only 17.7% higher than baseline while adapting to traffic conditions.
- In off-peak conditions, it provides travel times close to the optimal Traffic-Adaptive approach (2.3% longer) while maintaining awareness of carbon impacts.
- In mixed conditions, it achieves the best balance of travel time and emissions awareness.

2) Practical Trade-offs: Several practical trade-offs must be considered:

- **Emissions vs. Time**: There is an inherent trade-off between minimizing carbon emissions and travel time, particularly in congested conditions.
- **Vehicle-Specific Strategies**: Different vehicle types show varying benefits from carbon-aware adaptive routing, suggesting vehicle characteristics should be considered when deploying such systems.

3) Framework Effectiveness: The two-layer framework described in the methodology section proves effective in integrating carbon awareness with real-time traffic adaptation. Our results validate several key aspects:

- The separation between the Link Layer and Transport Layer facilitates integration of multiple optimization criteria.
- Real-time traffic data enables responsive adaptation to changing conditions, as evidenced by performance improvements in off-peak and mixed traffic scenarios.
- The carbon emission calculator successfully incorporates vehicle-specific factors, as demonstrated by differentiated performance across vehicle types.

In conclusion, our Carbon-Aware Adaptive Routing Protocol successfully balances emission reduction with travel time optimization, offering a practical solution for sustainable logistics in Cyber-Physical Internet networks. While trade-offs exist, the protocol provides a flexible framework to optimize routing based on specific sustainability goals and operational constraints.

V. CONCLUSION

This paper presented a Carbon-Aware Adaptive Routing Protocol with Real-Time Traffic Information for Cyber-Physical Internet networks. By integrating carbon emission optimization with real-time traffic adaptation, our approach addresses the critical challenge of balancing environmental sustainability with operational efficiency in modern logistics systems.

Our research makes several significant contributions: (1) a novel two-layer architecture integrating carbon emission metrics with real-time traffic data; (2) a Carbon-Aware Adaptive routing algorithm using a multi-objective approach to balance emissions and travel time; (3) a comprehensive carbon emission calculation methodology accounting for various vehicle-specific factors; and (4) a realistic simulation framework for the Greater Bay Area transportation network.

Our experimental evaluation revealed important findings. In mixed conditions, which most closely represent real-world operations, our approach achieved the lowest average travel time (75.2 minutes) while maintaining carbon awareness. The results demonstrate a clear emissions-time trade-off, with different vehicle types showing varying benefits from carbon-aware adaptive routing. Light trucks and heavy trucks achieved significant time savings (20

The practical implications of our work include enhanced decision support for logistics operators, improved resilience to changing traffic conditions, better environmental reporting capabilities, and seamless integration potential with existing systems. By adjusting the carbon weight parameter, operators can align routing strategies with their specific sustainability goals and service requirements.

We acknowledge limitations in our current approach, including emission model simplifications, limited traffic prediction capabilities, and static carbon weight parameters. Future research directions include developing enhanced emission models that account for additional factors, creating algorithms that dynamically adjust carbon weight parameters, extending the protocol to incorporate multi-modal transportation options, applying machine learning techniques for traffic prediction, investigating collaborative routing approaches, and conducting real-world validation studies.

The development of sustainable logistics systems is increasingly critical as organizations face pressure to reduce environmental impact while maintaining efficiency. Our Carbon-Aware Adaptive Routing Protocol represents a significant step toward addressing this challenge, demonstrating that logistics systems can reduce environmental impact without significantly compromising performance, particularly in mixed traffic conditions that characterize real-world operations.

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