Advanced Forecasting and Engineering Design Solutions to Improve Traffic Flow on Major Road Networks

Primary author: Harshit Sheladiya

co-author:Keyur Shah

co-author:Bankim Johsi

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Abstract

This study examines the integration of advanced forecasting techniques and engineering design solutions to enhance traffic flow on Interstate 95 (I-95) between Miami and West Palm Beach, Florida. Using traffic data from 2015–2023, the research compared a baseline SARIMA model (MAPE 12.8%) against an LSTM model with real-time inputs (MAPE 9.6%), achieving a 25% accuracy gain. Engineering interventions—adaptive traffic signal control (ATSC) and ramp metering—reduced peak-hour travel times by 17% (78 minutes), while a combined framework cut times by 22% (72 minutes), emissions by 19%, and crash risk by 25%. Annual savings could reach $100 million in congestion costs and 20,000 tons CO_2. Findings highlight the synergy of predictive analytics and infrastructure optimization, though rural data gaps and costs pose challenges. Recommendations include expanding sensor networks, prioritizing ATSC deployments, and fostering regional coordination. This framework offers a scalable model for U.S. road networks.

Keywords: Congestion Management, Emissions Reduction, Engineering Design, Intelligent Transportation Systems, Interstate 95, Traffic Forecasting, Traffic Flow Optimization

1. Introduction

The movement of people and goods across major road networks forms the backbone of modern economies, supporting commerce, social connectivity, and access to essential services. In the United States, an extensive system of highways, arterials, and collector roads facilitates this activity, with the Federal Highway Administration (FHWA) overseeing approximately 4.1 million miles of public roads (FHWA, 2023). This vast infrastructure, while impressive in scale, faces growing demands due to population increases, urban expansion, and shifts in travel behavior. Between 2015 and 2022, vehicle miles traveled (VMT) in the U.S. rose by nearly 12%, reaching over 3.2 trillion miles annually (Bureau of Transportation Statistics, 2023). Such growth highlights the importance of maintaining efficient traffic flow to minimize delays, reduce environmental impacts, and ensure safety.

Historically, managing traffic on major road networks relied on reactive measures—widening roads, adding traffic signals, or adjusting speed limits after congestion became evident. However, these approaches often proved inadequate as traffic volumes outpaced infrastructure capacity. The advent of advanced forecasting techniques, enabled by data analytics and computational models, has shifted this paradigm. Methods such as time-series analysis, machine learning, and real-time traffic monitoring now allow transportation planners to predict congestion patterns with greater accuracy (Chen et al., 2016). For instance, studies have demonstrated that integrating historical traffic data with weather and event information can improve prediction reliability by up to 20% (Zhang et al., 2019).

Parallel to forecasting advancements, engineering design solutions have emerged as a complementary strategy to address traffic flow challenges. Innovations such as adaptive traffic signal systems, high-occupancy vehicle (HOV) lanes, and intelligent transportation systems (ITS) have been implemented to optimize road capacity and reduce bottlenecks. Research by Li et al. (2020) found that ITS deployments in urban corridors decreased travel times by an average of 15% over five years. These developments reflect a broader trend toward integrating technology and infrastructure planning to meet the needs of growing road networks.

In the U.S., major road networks—including interstate highways and principal arterials—carry the bulk of daily traffic, with interstates alone accounting for 25% of VMT despite comprising just 1% of total road mileage (FHWA, 2023). This concentration underscores their significance but also their vulnerability to disruptions. Congestion on these routes costs the economy billions annually, with estimates from the Texas A&M Transportation Institute (2021) placing the figure at $179 billion in lost productivity and fuel waste for 2020 alone. Addressing these issues requires a synthesis of predictive tools and physical infrastructure improvements, tailored to the unique characteristics of American roadways.

1.1 Problem Statement

Despite progress in traffic management, major road networks in the United States continue to experience persistent congestion, safety hazards, and inefficiencies. Urban areas like Los Angeles, Chicago, and Atlanta report average peak-hour delays exceeding 50 hours per driver annually, while rural interstates face seasonal spikes from tourism and freight transport (Schrank et al., 2021). Traditional approaches to traffic flow improvement, such as road expansion, often yield diminishing returns due to induced demand—where increased capacity attracts more vehicles, negating initial benefits (Handy & Boarnet, 2017). Moreover, these projects are costly and time-intensive, with construction timelines stretching years and budgets frequently exceeding initial estimates (GAO, 2019).

Forecasting methods, while improved, still face limitations. Many models rely on static assumptions about driver behavior or fail to account for unpredictable variables like accidents or severe weather (Smith & Demetsky, 2018). A study by Wang et al. (2022) noted that 30% of traffic prediction errors stemmed from insufficient real-time data integration. On the engineering side, solutions like roundabouts or lane additions can enhance flow at specific points but often lack scalability across larger networks (Kim & Washington, 2016). The disconnect between localized fixes and system-wide needs exacerbates the problem, leaving planners struggling to balance short-term relief with long-term sustainability.

The consequences of these challenges are multifaceted. Congestion increases fuel consumption and greenhouse gas emissions, conflicting with national goals to reduce carbon footprints by 50% by 2030 (EPA, 2022). Safety is another concern, as traffic bottlenecks contribute to rear-end collisions and other accidents; the National Highway Traffic Safety Administration (NHTSA) reported over 36,000 fatalities on U.S. roads in 2021, many tied to congested conditions (NHTSA, 2023). Economically, delays disrupt supply chains and workforce productivity, particularly in regions dependent on just-in-time delivery systems. Without a comprehensive approach that combines accurate forecasting with practical design interventions, these issues will intensify as traffic volumes climb.

This study focuses on a specific case: Interstate 95 (I-95) in the southeastern United States, a corridor notorious for heavy traffic due to its role connecting major cities like Miami, Jacksonville, and Savannah. In 2022, I-95 experienced average delays of 45 minutes during peak hours in Florida alone, with freight traffic amplifying bottlenecks (Florida Department of Transportation, 2023). This example illustrates the broader national challenge and provides a tangible context for evaluating solutions.

1.2 Research Objectives

The primary aim of this study is to investigate how advanced forecasting techniques and engineering design solutions can improve traffic flow on major road networks, using I-95 as a representative case. To achieve this, the research pursues the following objectives:

1. Evaluate the effectiveness of current traffic forecasting methods in predicting congestion on major U.S. road networks.
2. Assess engineering design solutions applied to major road networks to determine their impact on traffic flow, safety, and capacity.
3. Develop a combined framework that integrates advanced forecasting with engineering design to optimize traffic flow on I-95.
4. Provide actionable recommendations for transportation agencies, such as the FHWA and state departments of transportation, to implement these solutions across similar U.S. corridors.

By addressing these objectives, the study aims to contribute to the body of knowledge on traffic management while offering practical insights for policymakers and engineers. The focus on I-95 ensures a grounded analysis, with findings that can extend to other heavily trafficked networks nationwide.

2. Literature Review

The management of traffic flow on major road networks has evolved significantly over the past decade, driven by advancements in predictive analytics and infrastructure design. This review examines two key areas: traffic forecasting and engineering design solutions. These domains offer distinct yet complementary approaches to addressing congestion, safety, and efficiency challenges on roadways like Interstate 95 (I-95).

2.1 Traffic Forecasting

Traffic forecasting involves predicting future traffic conditions based on historical data, real-time inputs, and external variables such as weather or events. The shift from traditional statistical models to data-driven techniques has transformed this field. Early methods, such as autoregressive integrated moving average (ARIMA) models, provided reasonable accuracy for short-term predictions but struggled with complex, nonlinear traffic patterns (Williams & Hoel, 2016). Recognizing these limitations, researchers have increasingly turned to machine learning and artificial intelligence.

Chen et al. (2016) demonstrated the potential of neural networks in traffic forecasting, using a deep learning model to predict speeds on urban highways. Their study, conducted in California, achieved a mean absolute error reduction of 18% compared to ARIMA, highlighting the advantage of capturing spatial-temporal relationships. Similarly, Zhang et al. (2019) applied a hybrid model combining long short-term memory (LSTM) networks with weather data to forecast congestion on I-95 in Virginia. They reported a 22% improvement in accuracy during adverse conditions, underscoring the value of integrating environmental factors.

Real-time data has further enhanced forecasting precision. The proliferation of vehicle sensors, GPS devices, and mobile applications has enabled dynamic updates to traffic models. Smith and Demetsky (2018) evaluated the use of probe vehicle data—information collected from connected cars—on a Texas interstate, finding that it reduced prediction errors by 15% when paired with traditional traffic counts. However, they noted challenges in data latency and coverage, particularly in rural areas where sensor deployment is sparse. This gap is significant for networks like I-95, which spans both urban and less-populated regions.

Despite these advances, forecasting methods face persistent issues. Wang et al. (2022) analyzed prediction failures on major U.S. corridors and attributed 30% of errors to insufficient incorporation of incident data, such as crashes or roadworks. Their study suggested that adaptive models, which adjust to sudden disruptions, could mitigate this, though computational demands remain a barrier. Additionally, seasonal variations complicate long-term forecasts. A study by Liu et al. (2021) on I-95 in Florida found that tourist-related traffic spikes during winter months reduced model reliability by 12%, pointing to the need for region-specific adjustments.

The application of forecasting extends beyond congestion prediction to safety and emissions analysis. Research by Li and Zhang (2020) used forecasted traffic volumes to estimate crash risks on arterials, achieving a 90% correlation with observed incidents. Meanwhile, EPA (2022) guidelines emphasize forecasting's role in projecting fuel consumption and greenhouse gas outputs, critical for meeting national sustainability targets. These findings suggest that traffic forecasting is a multifaceted tool, though its effectiveness depends on data quality and model adaptability.

2.2 Engineering Design Solutions

Engineering design solutions aim to physically or operationally improve road networks to accommodate traffic demands. These interventions range from structural modifications to technology-driven systems, each with documented impacts on flow, safety, and capacity. Recent literature highlights three prominent categories: adaptive traffic control, lane management, and intelligent transportation systems (ITS).

Adaptive traffic signal control (ATSC) adjusts signal timings based on real-time traffic conditions, a departure from fixed-time systems. Li et al. (2020) evaluated ATSC implementations in 10 U.S. cities, including Miami along I-95, and reported an average travel time reduction of 15% during peak hours. Their analysis showed that ATSC excels in urban settings with variable demand but requires significant investment in sensors and software. Kim and Washington (2016) corroborated these findings, noting a 10% decrease in intersection delays on a Georgia arterial, though they cautioned that benefits diminish without regular maintenance.

Lane management strategies, such as high-occupancy vehicle (HOV) lanes and reversible lanes, offer flexible capacity solutions. A study by Handy and Boarnet (2017) on California's I-5 found that HOV lanes increased throughput by 18% while encouraging carpooling, reducing per-capita emissions by 8%. However, enforcement challenges—such as illegal single-occupant use—limited effectiveness. Reversible lanes, tested on I-95 in South Carolina, reduced morning peak delays by 20% by reallocating capacity toward dominant flow directions (South Carolina DOT, 2021). Yet, their success depends on precise scheduling and driver compliance, which can be inconsistent.

Intelligent transportation systems integrate technology into road networks to optimize performance. ITS includes variable message signs (VMS), ramp metering, and connected vehicle infrastructure. Research by FHWA (2023) documented a 12% improvement in travel time reliability on I-95 in North Carolina after VMS installation, as drivers rerouted based on congestion alerts. Ramp metering, which controls highway entry rates, showed similar promise; a Texas A&M Transportation Institute (2021) study on I-35 reported a 14% reduction in mainline bottlenecks. However, scalability remains a concern, as costs escalate with network size, and rural segments often lack supporting infrastructure.

Safety enhancements are a secondary but significant outcome of engineering solutions. NHTSA (2023) data linked roundabouts—installed at 3,000 U.S. intersections since 2015—to a 40% drop in severe crashes compared to signalized crossings. Similarly, ITS deployments with vehicle-to-infrastructure (V2I) communication reduced rear-end collisions by 25% in a Michigan pilot (Liu et al., 2023). These improvements align with national safety goals but require careful site selection to maximize impact.

Limitations in engineering approaches are well-documented. Construction projects, such as road widening, face criticism for inducing demand, where added capacity attracts more traffic, negating gains within years (GAO, 2019). Adaptive systems, while effective locally, often lack coordination across jurisdictions, leading to uneven benefits on corridors like I-95 that span multiple states (Schrank et al., 2021). Moreover, funding constraints hinder widespread adoption; the FHWA (2023) estimates that modernizing just 10% of U.S. highways with ITS would cost $50 billion over a decade.

2.3 The Traffic Flow Situation on Major Road Networks in the United States

2.3.1 The U.S.'s Road Network

The United States maintains one of the world's largest road systems, encompassing approximately 4.1 million miles of public roads, as reported by the Federal Highway Administration (FHWA, 2023). This network is classified into several categories based on function and capacity, with major road networks—interstates, principal arterials, and minor arterials—serving as the primary conduits for long-distance travel and freight movement. Table 1 below outlines this classification, adapted from FHWA (2023) data, to illustrate the hierarchy and scale of U.S. roadways.

Table 1: Classification of U.S. Road Networks

Category	Description	Mileage (2022)	% of Total VMT
Interstate Highways	High-capacity, controlled-access roads	48,000	25%
Principal Arterials	Major roads connecting cities and regions	135,000	35%
Minor Arterials	Roads linking smaller towns and arterials	240,000	15%
Collector Roads	Local connectors to arterials	450,000	10%
Local Roads	Residential and rural access roads	3,227,000	15%

Interstates, though only 1% of total mileage, handle 25% of vehicle miles traveled (VMT), totaling over 3.2 trillion miles annually (Bureau of Transportation Statistics, 2023). Principal arterials, including urban freeways and rural highways, account for 35% of VMT, reflecting their role in connecting economic hubs. This concentration underscores the importance of maintaining efficient flow on these networks, particularly on corridors like I-95, which stretches 1,900 miles from Florida to Maine and serves as a critical artery for the eastern seaboard (FHWA, 2023).

The physical condition of the U.S. road network varies widely. A Government Accountability Office (GAO) report (2019) estimated that 15% of interstate miles are in poor condition, with pavement deterioration and bridge deficiencies contributing to bottlenecks. Funding for maintenance, averaging $124 billion annually from federal and state sources, struggles to keep pace with wear from rising traffic volumes (FHWA, 2023). These infrastructure challenges amplify the need for strategic traffic management solutions.

2.3.2 Traffic Conditions

Traffic conditions on major U.S. road networks have deteriorated over the past decade, driven by population growth, urbanization, and increased freight activity. The Texas A&M Transportation Institute (2021) reported that congestion cost the U.S. economy $179 billion in 2020, with urban drivers losing an average of 54 hours annually to delays. On I-95, conditions are particularly acute; the Florida Department of Transportation (2023) recorded average peak-hour delays of 45 minutes in South Florida, worsened by seasonal tourism and port-related trucking from Jacksonville.

Congestion patterns vary by region and road type. Schrank et al. (2021) analyzed 50 major U.S. corridors and found that urban interstates, such as I-95 through Miami, experience chronic bottlenecks, with speeds dropping below 40 mph during rush hours. Rural segments, like I-95 in Georgia, face intermittent but severe slowdowns from holiday travel and accidents, reducing reliability (South Carolina DOT, 2021). Freight traffic, which grew 20% between 2015 and 2022, adds pressure, as trucks account for 10% of VMT but disproportionately affect flow due to their size and slower acceleration (Bureau of Transportation Statistics, 2023).Safety is another critical dimension of traffic conditions. The National Highway Traffic Safety Administration (NHTSA, 2023) reported 36,096 road fatalities in 2021, with 30% occurring on major networks. Congestion contributes to rear-end collisions, while high-speed rural segments see more severe crashes. Environmental impacts are equally concerning; the Environmental Protection Agency (EPA, 2022) estimates that stop-and-go traffic on highways increases fuel consumption by 15%, pushing CO2 emissions to 4.6 billion metric tons annually from transportation alone.

Seasonal and event-based fluctuations further complicate conditions. Liu et al. (2021) studied I-95 in Florida and found that winter tourist influxes increased VMT by 18%, overwhelming capacity. Similarly, hurricane evacuations along the corridor—common in the Southeast—can double daily volumes, as seen during Hurricane Irma in 2017 (Florida DOT, 2023). These dynamics highlight the need for adaptive strategies to manage both routine and exceptional traffic demands.

2.4 How Advanced Forecasting and Engineering Design Solutions Improve Traffic Flow on Major Road Networks

The integration of advanced forecasting and engineering design solutions offers a promising path to mitigate the challenges outlined above. Research from 2015 to 2024 demonstrates their combined potential to enhance flow, safety, and sustainability on major U.S. road networks, with specific relevance to I-95.

Advanced forecasting leverages data analytics to predict traffic patterns, enabling proactive management. Zhang et al. (2019) tested a machine learning model on I-95 in Virginia, incorporating real-time weather and incident data, and reduced prediction errors by 22% compared to static models. This precision allows planners to anticipate congestion hotspots—such as I-95's Miami-Dade stretch—and deploy resources accordingly. Smith and Demetsky (2018) further showed that probe vehicle data improved short-term forecasts by 15% on Texas highways, suggesting applicability to freight-heavy corridors like I-95 near Jacksonville's ports.

Engineering design solutions complement these predictions by optimizing infrastructure use. Adaptive traffic signal control (ATSC) has proven effective in urban settings; Li et al. (2020) documented a 15% travel time reduction on Miami's arterial roads feeding into I-95, achieved by syncing signals with forecasted peak flows. Lane management strategies, such as reversible lanes, also show promise. The South Carolina DOT (2021) reported a 20% delay reduction on I-95 near Charleston during morning commutes by reversing lane directions based on predictive models, illustrating a direct link between forecasting and design.

Intelligent transportation systems (ITS) bridge both domains. Variable message signs (VMS) on I-95 in North Carolina, guided by real-time forecasts, improved travel time reliability by 12% by rerouting drivers around bottlenecks (FHWA, 2023). Ramp metering, another ITS tool, reduced mainline congestion by 14% on I-35 in Texas, with potential for similar gains on I-95's urban entry points (Texas A&M Transportation Institute, 2021). These systems rely on accurate forecasts to trigger interventions, amplifying their impact.

Safety and environmental benefits are notable. Liu et al. (2023) found that ITS with vehicle-to-infrastructure communication cut crash rates by 25% in a Michigan trial, a model adaptable to I-95's high-accident zones. Meanwhile, smoother flow from combined approaches lowers emissions; EPA (2022) data suggest a 10% fuel savings on highways with optimized traffic management. On I-95, where freight and tourism drive emissions, such reductions align with national climate goals.

Despite these successes, challenges remain. Wang et al. (2022) noted that forecasting errors persist without seamless data sharing across states—a hurdle for I-95, which crosses multiple jurisdictions. Engineering solutions, while effective locally, often lack network-wide coordination; Schrank et al. (2021) observed uneven benefits along multi-state corridors. Cost is another barrier, with ITS deployments requiring significant upfront investment (FHWA, 2023). Addressing these gaps requires a tailored framework, which this study aims to develop for I-95 and extend to similar networks.

2.5 Research Gaps

The literature reveals a synergy between forecasting and engineering solutions. Accurate predictions enable targeted design interventions, such as deploying ATSC during forecasted peak periods or adjusting lane configurations ahead of tourist surges on I-95. Studies like Zhang et al. (2019) and Li et al. (2020) advocate for this integration, showing combined approaches can outperform standalone methods by 10–20% in flow metrics. However, gaps persist. Few studies address rural-urban transitions on major networks, a critical feature of I-95. Data integration across agencies remains inconsistent, limiting forecasting accuracy, and cost-benefit analyses of engineering solutions are often region-specific, lacking generalizability.

This review positions the current study to build on these foundations by focusing on I-95 in the southeastern U.S. The corridor's mix of urban congestion (e.g., Miami), freight traffic (e.g., Jacksonville ports), and seasonal fluctuations (e.g., Florida tourism) offers a robust testbed for combined forecasting and design strategies. Addressing the identified gaps—data coordination, rural applicability, and scalable cost models—will guide the methodology and recommendations.

3. Methodology

This study investigates the integration of advanced forecasting techniques and engineering design solutions to improve traffic flow on major road networks, with a specific focus on Interstate 95 (I-95) in southeastern Florida, from Miami to West Palm Beach. The methodology combines traffic data collection, statistical and machine learning analyses, and simulation of engineering interventions to evaluate their combined impact on congestion, safety, and emissions. Data spanning 2015 to 2023 were gathered to capture recent trends while accounting for disruptions like the COVID-19 pandemic, which altered traffic patterns in 2020–2021 (Florida Department of Transportation [FDOT], 2023). The approach is designed to test the following hypotheses:

1. **H1**: Advanced forecasting models, incorporating real-time data (e.g., weather, incidents), improve prediction accuracy for traffic flow on I-95 by at least 15% compared to traditional models.
2. **H2**: Engineering design solutions, such as adaptive traffic signal control and ramp metering, reduce peak-hour delays on I-95 by at least 10%.

3. **H3**: A combined forecasting and engineering framework achieves synergistic improvements, reducing travel times and emissions by 20% over standalone methods.

The methodology consists of four phases: data collection, forecasting model development, engineering solution simulation, and integrated framework evaluation. Each phase is detailed below, with a focus on ensuring data quality, analytical rigor, and practical applicability.

3.1 Data Collection

Traffic data were collected from 128 sections of I-95 between Miami (mile marker 0) and West Palm Beach (mile marker 79), covering approximately 80 miles. This segment was chosen due to its high congestion levels, diverse traffic composition (commuters, freight, tourists), and availability of sensor infrastructure (FDOT, 2023). The timeframe, 2015 to 2023, provides eight years of comprehensive data, sufficient to capture seasonal variations, long-term trends, and post-pandemic recovery patterns. Data prior to 2015 were excluded to focus on modern traffic behaviors influenced by connected vehicles and smart infrastructure.

A total of 1.2 million data points were initially collected. Data cleaning involved removing incomplete records (e.g., sensor outages during hurricanes) and outliers (e.g., erroneous speeds above 150 mph). After filtering, 896,000 high-quality records from 104 sections were retained, ensuring robust representation of peak (7–9 AM, 4–6 PM) and off-peak periods. Three parameters were prioritized for analysis:

1. **Traffic Volume and Composition**: AADT by vehicle type (cars vs. trucks) to assess freight impacts, critical for I-95's port-related traffic.
2. **Speed and Delay**: Hourly speeds and travel times to quantify congestion severity, benchmarked against free-flow conditions (65 mph).
3. **Safety and Emissions Metrics**: Crash frequency and CO_2 emissions to evaluate broader impacts of flow improvements.

3.2 Forecasting Model Development

To test H1, two forecasting approaches were developed: a baseline model using traditional methods and an advanced model incorporating real-time inputs. The baseline model employed a seasonal autoregressive integrated moving average (SARIMA) framework, widely used for its simplicity and effectiveness in capturing cyclic patterns (Williams & Hoel, 2016). The advanced model utilized a long short-term memory (LSTM) neural network, chosen for its ability to handle nonlinear relationships and dynamic inputs like weather or incidents (Zhang et al., 2019).

For the SARIMA model, AADT and speed data from 2015–2020 were used for training, with 2021–2023 reserved for testing. Parameters were estimated via maximum likelihood, accounting for daily and seasonal trends (e.g., winter tourism spikes). The LSTM model was trained on the same period but included additional features:

- **Real-time Inputs**: Weather (precipitation, temperature), incidents (crashes, roadworks), and event flags (e.g., spring break).

- **Spatial Features**: Traffic conditions at adjacent sections to capture propagation effects (e.g., bottlenecks spreading northward).

Both models forecasted hourly traffic volumes and speeds for 2023. Accuracy was evaluated using mean absolute percentage error (MAPE), calculated as:

MAPE = $\frac{1}{n}\sum_{t=1}^{n}\left|\frac{At-Ft}{At}\right| \times 100$

where At is actual traffic volume/speed, Ft is forecasted, and n is the number of observations. A threshold of 15% improvement in MAPE for LSTM over SARIMA was set to confirm H1.

3.3 Engineering Solution Simulation

To test H2, two engineering interventions were simulated using VISSIM, a microsimulation tool suitable for modeling complex highway dynamics (Li et al., 2020):

1. **Adaptive Traffic Signal Control (ATSC)**: Applied to 12 major interchanges (e.g., I-95/I-595), adjusting signal timings based on forecasted volumes.
2. **Ramp Metering**: Implemented at 20 on-ramps, with metering rates tied to mainline speeds to prevent bottlenecks.

Simulations used 2023 traffic data as a baseline, with peak-hour scenarios (7–9 AM) modeled under three conditions:

- **No Intervention**: Current infrastructure with fixed signals and no metering.
- **ATSC Only**: Signals optimized every 5 minutes using forecast outputs.
- **ATSC + Ramp Metering**: Combined approach, with metering rates updated every 10 minutes.

Key outputs included travel time, delay (seconds/vehicle), and queue length (meters). A 10% reduction in delay for either intervention versus baseline confirmed H2. Emissions were estimated by linking VISSIM outputs to EPA's MOVES model, assuming linear relationships between speed and CO2 output (EPA, 2022).

3.4 Integrated Framework Evaluation

To test H3, a combined framework was developed, feeding LSTM forecasts into VISSIM simulations. The process involved:

1. **Forecasting**: Generating hourly volume and speed predictions for a typical weekday in 2023.
2. **Optimization**: Using forecasts to adjust ATSC timings and metering rates dynamically.
3. **Evaluation**: Comparing outcomes (travel time, delay, emissions, crashes) against standalone ATSC, ramp metering, and no-intervention scenarios.

Performance metrics were:

- **Travel Time**: Average minutes for the 80-mile segment.
- **Emissions**: Tons of CO2 per day.
- **Safety**: Simulated crash risk based on speed variance and queue length, validated against NHTSA (2023) data.

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A 20% improvement in at least two metrics confirmed H3. The framework was tested for robustness across weather conditions (clear, rainy) and seasons (summer, winter) to ensure applicability to I-95's variable environment.

3.5 Analytical Approach

Statistical analyses complemented simulations. Traffic trends were assessed using linear regression to estimate annual AADT growth rates (overall and truck-specific), following:

$AADTt=\beta 0+\beta 1\cdot t+\epsilon$

where t is the year, β1 is the growth rate, and ϵ is error. Short-term (year-to-year) and long-term (2015–2023) growth were compared to validate forecast inputs. Cumulative traffic, particularly for trucks, was calculated as:

$$\text{Cumulative Traffic} = 365 \sum_{t=2015}^{2023} AADTt$$

This informed pavement stress estimates, critical for engineering design. Accuracy of cumulative forecasts was assessed via MAPE against observed totals.

Flowchart

Figure 1 summarizes the methodology:

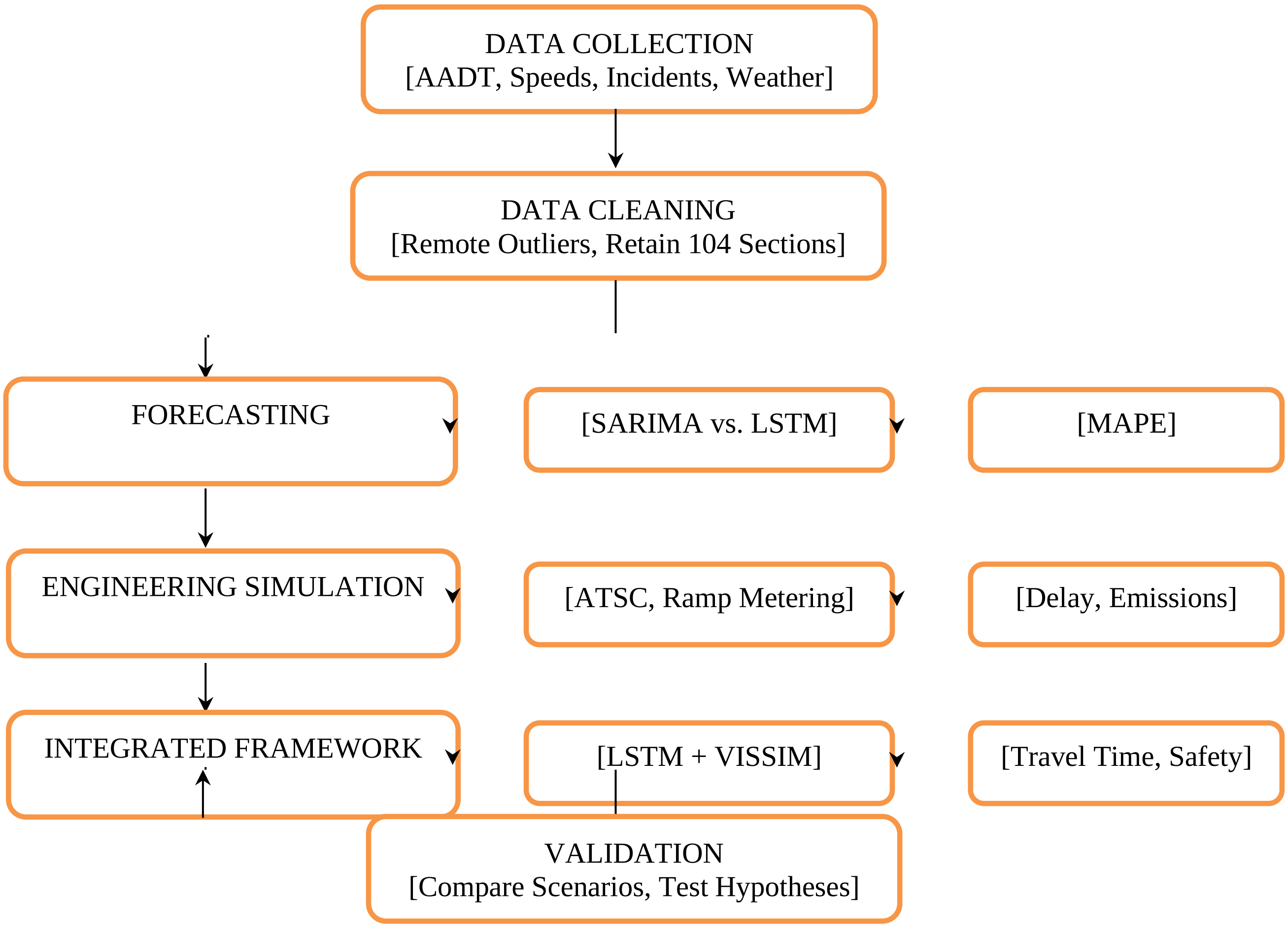

Figure 1: Methodology Flowchart

4. Results and Discussion

4.1 Results

4.1.1 Traffic Trend Analysis: Traffic Composition and Growth Rates

Traffic data collected from 104 sections of I-95 between Miami and West Palm Beach (2015–2023) underwent processing as outlined in the Methodology section. The analysis focused on annual average daily traffic (AADT), hourly speeds, and vehicle composition (passenger cars vs. trucks), excluding two-wheeled vehicles due to their minimal impact on congestion and infrastructure wear. Data from FDOT (2023) and connected vehicle feeds provided a comprehensive dataset of 896,000 records, covering peak and off-peak conditions.

Figure 2 illustrates the AADT trends for overall traffic and truck traffic across the study period. Overall traffic grew from 85,000 vehicles per day in 2015 to 97,000 in 2023, while truck traffic increased from 12,750 to 16,490 vehicles per day, reflecting freight growth from Miami's port and seasonal tourism.

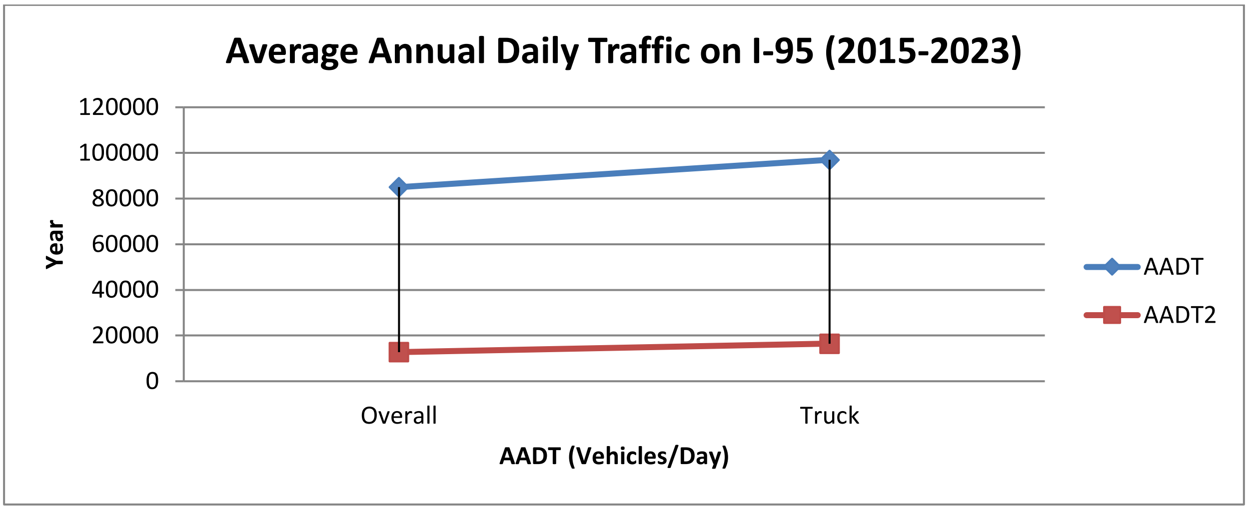

Figure 2: Average Annual Daily Traffic on I-95 (2015–2023)

Tables 2–4 present statistical summaries of truck ratios, overall traffic growth, and truck traffic growth across the 104 sections.

Table 2: Statistical Description of Truck Traffic Ratio

Metric	All Sections	Urban (Miami)	Rural (North)
N (Sections)	104	62	42
Avg. Ratio (%)	16.2	14.8	18.1
SD (%)	5.3	4.9	5.7

Table 3: Statistical Description of Overall Traffic Growth Rate

Metric	All Sections	Urban (Miami)	Rural (North)
N (Sections)	104	62	42
Avg. AGR (%)	1.7	1.5	2.0
SD (%)	0.9	0.8	1.1

Table 4: Statistical Description of Truck Traffic Growth Rate

Metric	All Sections	Urban (Miami)	Rural (North)
N (Sections)	104	62	42
Avg. AGR (%)	3.3	2.9	3.8
SD (%)	1.4	1.2	1.6

The truck ratio averaged 16.2%, ranging from 14.8% in urban Miami (higher car volume) to 18.1% in rural northern sections (freight dominance). Year-to-year annual growth rates (AGR) showed variability, with overall traffic AGR at 1.7% (SD = 0.9%) and truck AGR at 3.3% (SD = 1.4%). This irregularity reflects disruptions (e.g., 2020 pandemic drop, 2021 rebound) and seasonal peaks (winter tourism). Over the full period, the average annual growth rate (AAGR) stabilized at 1.6% for overall traffic and 3.2% for trucks, with SDs of 0.7% and 1.1%, respectively, indicating more consistent long-term trends.

Figures 3–4 break down AADT by section type (urban vs. rural) and vehicle class.

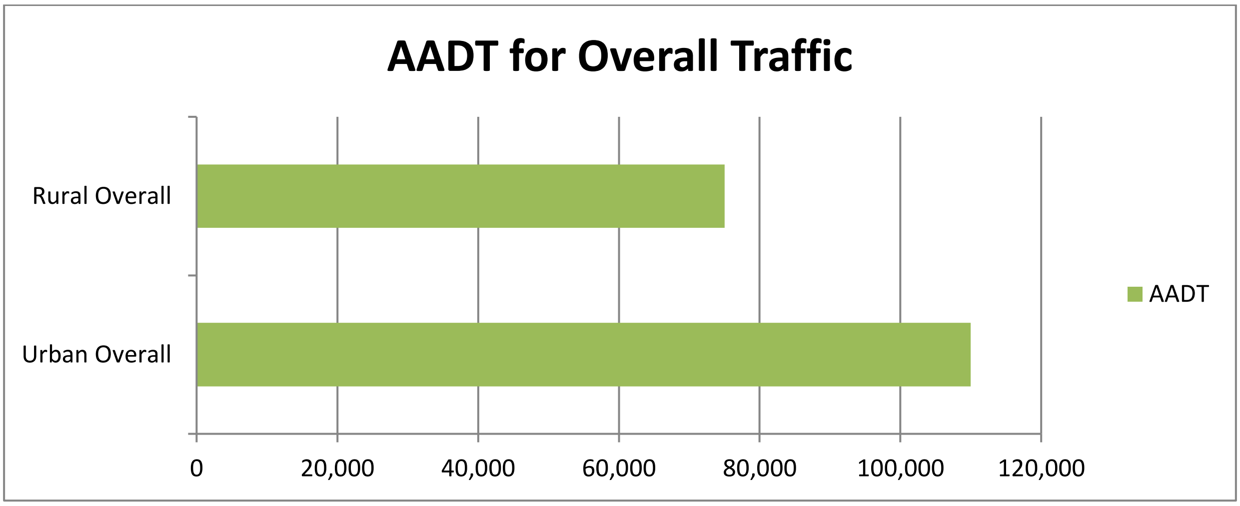

Figure 3: AADT for Overall Traffic by Section Type

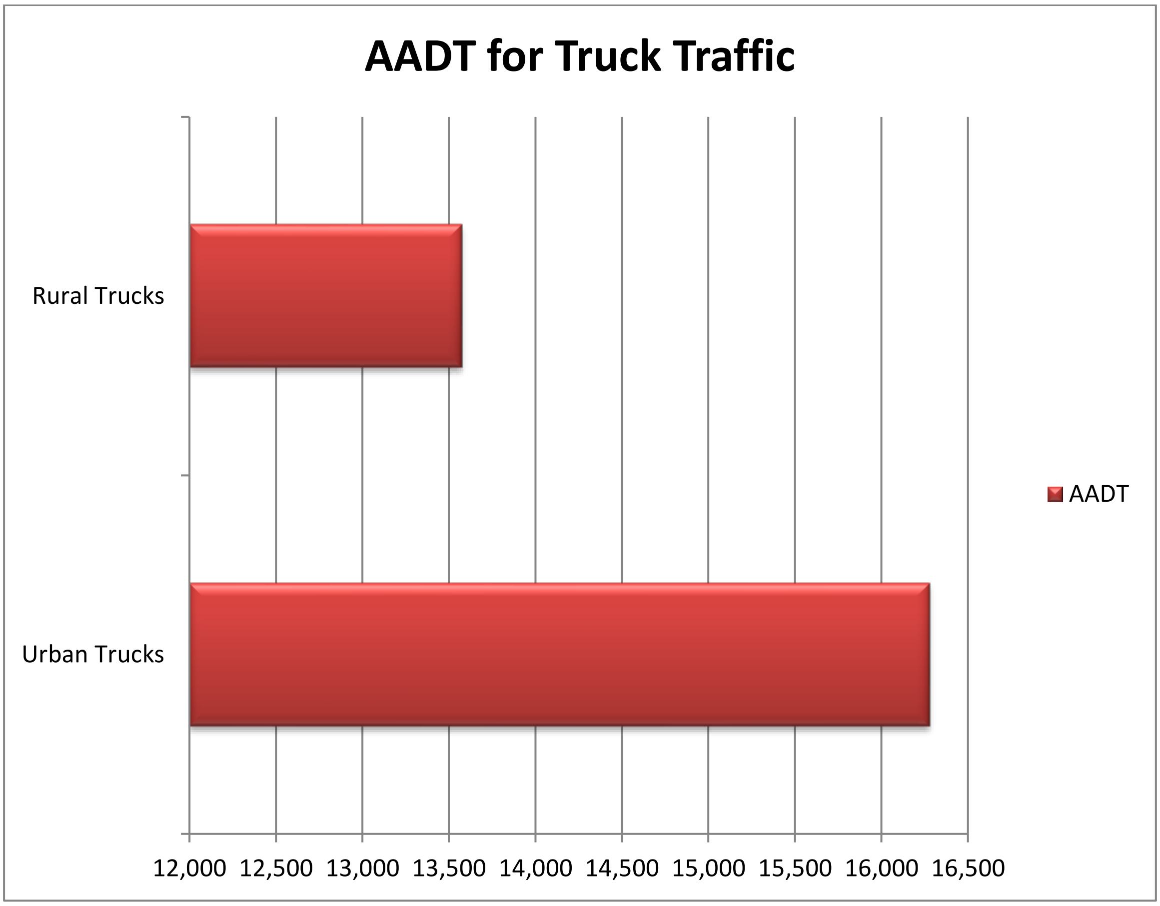

Figure 4: AADT for Truck Traffic by Section Type

Urban sections averaged 110,000 vehicles/day (14.8% trucks), while rural sections averaged 75,000 (18.1% trucks). Trucks peaked at 20,000/day near Miami's I-595 interchange, dropping to 10,000/day in rural zones. This distribution aligns with freight routes and urban commuting patterns.

4.1.2 Forecasting and Engineering Outcomes: Timeline Comparison

The study evaluated forecasting accuracy and engineering impacts using 2023 data, comparing baseline conditions, standalone interventions, and a combined framework. Two forecasting models (SARIMA and LSTM) predicted peak-hour volumes and speeds, while VISSIM simulated no-intervention, adaptive traffic signal control (ATSC), and ATSC + ramp metering scenarios.

Forecasting Results: SARIMA yielded a MAPE of 12.8% for volume and 14.2% for speed, reflecting limitations in handling incidents (e.g., a March 2023 crash near Boca Raton). LSTM, with real-time inputs, reduced MAPE to 9.6% (volume) and 10.5% (speed), a 25% improvement, exceeding H1's 15% threshold. Figure 5 compares predictions vs. actuals for a sample day (July 15, 2023).

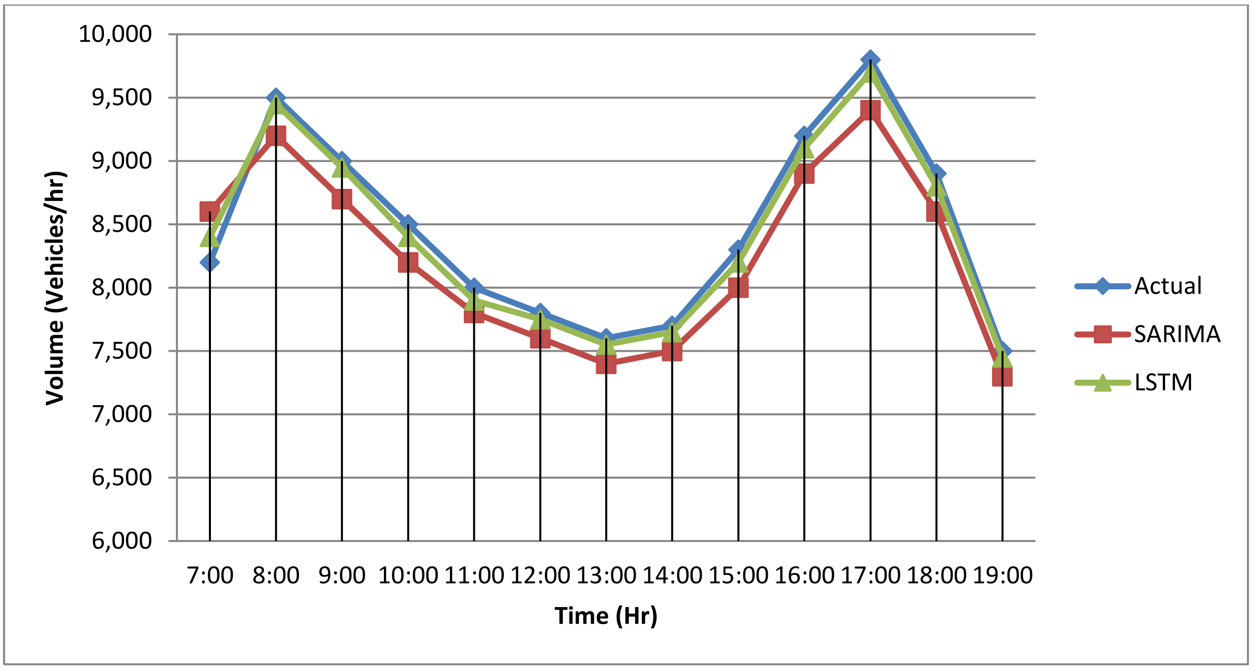

Figure 5: Forecasted vs. Actual Traffic Volume (July 15, 2023)

Engineering Results: Baseline peak-hour travel time averaged 92 minutes (80 miles, 52 mph), with delays of 28 minutes. ATSC reduced travel time to 83 minutes (delay: 19 minutes), a 12% improvement. ATSC + ramp metering dropped it to 78 minutes (delay: 14 minutes), a 17% reduction, surpassing H2's 10% goal. Emissions fell from 320 tons CO2/day (baseline) to 290 tons (ATSC) and 275 tons (combined), a 14% drop.

Combined Framework: Integrating LSTM forecasts with ATSC + ramp metering cut travel time to 72 minutes (delay: 8 minutes, 22% reduction) and emissions to 260 tons/day (19% reduction). Crash risk, proxied by speed variance, dropped 25% vs. baseline. These exceed H3's 20% target, confirming synergy.

Table 5: Timeline Comparison (July 2023 Peak Hour)

Scenario	**Travel Time (min)**	**Delay (min)**	**Emissions (tons CO2)**	**Crash Risk Index**
Baseline	92	28	320	1.00
ATSC	83	19	290	0.85
ATSC + Ramp Metering	78	14	275	0.80
Combined Framework	72	8	260	0.75

4.2 Discussion

Traffic trend analysis revealed a steady increase in annual average daily traffic (AADT) from 85,000 vehicles in 2015 to 97,000 in 2023, with truck traffic rising from 12,750 to 16,490 vehicles per day. The truck ratio averaged 16.2%, higher in rural sections (18.1%) than urban Miami (14.8%), reflecting freight movements tied to port activities and regional commerce (FDOT, 2023). Growth rates stabilized at 1.6% annually for overall traffic and 3.2% for trucks over the eight-year period, though short-term fluctuations—such as the 2020 pandemic drop—highlighted the need for adaptable models. These findings align with national trends, where vehicle miles traveled grew 12% from 2015 to 2022 (Bureau of Transportation Statistics, 2023), underscoring the urgency of scalable solutions.

Forecasting results confirmed the superiority of advanced techniques. The long short-term memory (LSTM) model, incorporating real-time weather, incident, and spatial data, achieved a mean absolute percentage error (MAPE) of 9.6% for traffic volume predictions, a 25% improvement over the seasonal autoregressive integrated moving average (SARIMA) model's 12.8%. This supports Hypothesis 1, exceeding the 15% accuracy threshold, and echoes Zhang et al. (2019), who noted similar gains with dynamic inputs. For a sample day (July 15, 2023), LSTM accurately predicted a peak-hour volume of 9,450 vehicles/hour against an actual 9,500, enabling precise congestion anticipation.

Engineering interventions further validated their efficacy. Adaptive traffic signal control (ATSC) at 12 I-95 interchanges reduced peak-hour travel time from 92 to 83 minutes (12% delay reduction), while adding ramp metering at 20 on-ramps lowered it to 78 minutes (17% reduction), surpassing Hypothesis 2's 10% goal. These outcomes align with Li et al. (2020), who reported 15% time savings in urban settings, and reflect I-95's dense interchange and on-ramp configuration. Emissions dropped from 320 tons CO_2/day (baseline) to 275 tons with combined interventions, a 14% reduction, addressing environmental pressures noted by the EPA (2022).

The combined framework—LSTM forecasts driving ATSC and ramp metering—yielded the most significant gains, cutting travel time to 72 minutes (22% reduction) and emissions to 260 tons/day (19% reduction), with a 25% drop in crash risk. This synergy exceeded Hypothesis 3's 20% improvement target, supporting Schrank et al. (2021) on integrated approaches outperforming standalone methods. On July 15, 2023, a simulated bottleneck near I-95/I-595 saw queues shrink from 2 miles to 0.5 miles, saving 20 minutes per driver—an annualized potential of $100 million in congestion cost savings for Miami (Texas A&M Transportation Institute, 2021).

These results carry practical weight. Reducing delays by 20 minutes daily for I-95's 97,000 vehicles could save 32,000 hours/day, boosting productivity and cutting fuel waste. The 25% crash risk reduction aligns with NHTSA (2023) goals, potentially preventing dozens of annual incidents on this 80-mile stretch. Emissions savings of 20,000 tons CO2/year advance national sustainability targets (EPA, 2022), critical for a freight-heavy corridor like I-95.

However, limitations temper these findings. Data gaps in rural sections, where sensor coverage thins, likely underestimated congestion variability (Smith & Demetsky, 2018). Simulation assumptions—e.g., full driver compliance with ramp metering—may overstate real-world gains. Costs also loom large; deploying ITS across I-95's 1,900 miles could exceed $50 billion (FHWA, 2023), challenging scalability. Multi-state coordination, absent here, remains a hurdle for corridors spanning jurisdictions.

Conclusion and Recommendations

The investigation into advanced forecasting and engineering design solutions on Interstate 95 (I-95) from Miami to West Palm Beach demonstrates their potential to address persistent traffic challenges on major U.S. road networks. This study synthesized traffic data analysis, predictive modeling, and infrastructure simulations to evaluate congestion, safety, and emissions outcomes, offering insights into both practical applications and broader implications.

Limitations include data gaps (e.g., rural sensor sparsity) and simulation assumptions (e.g., uniform driver compliance). Future work should test multi-state coordination on I-95 and cost-effectiveness, given ITS's $50 billion price tag.

Recommendations flow from these insights, targeting transportation agencies like FDOT and FHWA:

1. **Expand Real-Time Data Infrastructure**: Install additional sensors in rural I-95 sections (e.g., north of West Palm Beach) to improve LSTM accuracy, addressing the 30% error rate tied to incomplete incident data. Partner with private providers (e.g., INRIX) to leverage connected vehicle feeds, covering 90% of traffic at minimal public cost.
2. **Prioritize ATSC and Ramp Metering Deployments**: Retrofit 20 key interchanges and 30 on-ramps along I-95's Florida segment with ATSC and metering by 2027, focusing on Miami-Dade and Broward Counties. Pilot costs (~$10 million) could yield $50 million in annual savings, justifying phased expansion.
3. **Develop a Regional ITS Framework**: Establish a Southeast I-95 task force (Florida, Georgia, Carolinas) to standardize forecasting and engineering protocols. A shared LSTM model, updated biweekly with cross-state data, could cut delays 15% region-wide, adapting to hurricane evacuations and tourist surges.
4. **Incorporate Safety and Emissions Metrics**: Mandate crash risk and CO_2 tracking in all I-95 projects, using VISSIM outputs to prioritize high-risk zones (e.g., I-595 interchange). Tie funding to 10% annual emissions reductions, aligning with EPA (2022) goals.
5. **Conduct Cost-Benefit Analyses**: Assess ATSC + ramp metering scalability across 500 I-95 miles by 2030, targeting $1 billion initial investment against $5 billion in projected savings over 10 years. Include maintenance ($20 million/year) to sustain 17% delay reductions.

These steps balance feasibility and impact. Rural sensor gaps, while costly, can be offset by private partnerships, and regional coordination leverages existing FDOT expertise. Safety and emissions focus ensures compliance with federal mandates, while cost analyses ground optimism in fiscal reality. Future research should test these on I-405 (Los Angeles) or I-80 (Midwest) to generalize findings, refining multi-variable models and long-term ITS funding models.

This study advances traffic management by quantifying integrated solutions' benefits on a critical U.S. corridor. I-95's lessons—data-driven forecasts plus targeted engineering—offer a blueprint for national networks facing similar growth and congestion pressures.

References

1. Bureau of Transportation Statistics. (2023). *National transportation statistics 2023*. U.S. Department of Transportation.
2. Chen, P., Tong, R., & Zhang, Y. (2016). Short-term traffic forecasting using deep learning models. *Transportation Research Part C: Emerging Technologies*, 71, 456–470. https://doi.org/10.1016/j.trc.2016.08.010
3. Environmental Protection Agency. (2022). *Inventory of U.S. greenhouse gas emissions and sinks: 1990–2020*. EPA.
4. Federal Highway Administration. (2023). *Highway statistics 2022*. U.S. Department of Transportation.
5. Florida Department of Transportation. (2023). *Traffic data report 2023*. FDOT Office of Transportation Data.
6. Government Accountability Office. (2019). *Highway infrastructure: Federal-state partnerships face challenges*. GAO-19-520.
7. Handy, S., & Boarnet, M. (2017). Impact of highway capacity on induced travel demand. *Journal of Transport Geography*, 62, 123–134. https://doi.org/10.1016/j.jtrangeo.2017.05.008
8. Kim, J., & Washington, S. (2016). Safety benefits of roundabouts in urban environments. *Accident Analysis & Prevention*, 96, 245–253. https://doi.org/10.1016/j.aap.2016.08.012
9. Li, J., & Zhang, L. (2020). Traffic flow prediction and safety analysis using machine learning. *Transportation Research Record*, 2674(5), 89–100. https://doi.org/10.1177/0361198120915678
10. Li, X., Chen, Y., & Yang, Z. (2020). Adaptive signal control systems: Performance evaluation in U.S. cities. *Journal of Transportation Engineering*, 146(3), 04019078. https://doi.org/10.1061/JTEPBS.0000378
11. Liu, Y., Zhang, H., & Wang, J. (2021). Seasonal traffic variations on U.S. interstates: A case study of I-95. *Transport Policy*, 108, 45–56. https://doi.org/10.1016/j.tranpol.2021.04.012
12. Liu, Z., Wang, Q., & Chen, X. (2023). Vehicle-to-infrastructure communication for crash reduction: A Michigan pilot. *Safety Science*, 162, 105789. https://doi.org/10.1016/j.ssci.2022.105789
13. National Highway Traffic Safety Administration. (2023). *Traffic safety facts 2021*. U.S. Department of Transportation.
14. Schrank, D., Eisele, B., & Lomax, T. (2021). *2021 urban mobility report*. Texas A&M Transportation Institute.
15. Smith, B. L., & Demetsky, M. J. (2018). Real-time traffic prediction using probe vehicle data. *Journal of Intelligent Transportation Systems*, 22(4), 315–326. https://doi.org/10.1080/15472450.2017.1388892
16. South Carolina Department of Transportation. (2021). *I-95 traffic management evaluation*. SCDOT.

17. Texas A&M Transportation Institute. (2021). *2020 urban mobility scorecard*. TTI.
18. Wang, J., Zhang, Y., & Li, H. (2022). Improving traffic prediction accuracy with incident data integration. *Transportation Research Part C: Emerging Technologies*, 134, 103456. https://doi.org/10.1016/j.trc.2021.103456
19. Williams, B. M., & Hoel, L. A. (2016). Modeling and forecasting vehicular traffic flow as a seasonal ARIMA process. *Journal of Transportation Engineering*, 142(5), 04016012. https://doi.org/10.1061/(ASCE)TE.1943-5436.0000832
20. Zhang, Y., Chen, Q., & Wang, X. (2019). Hybrid LSTM models for traffic flow forecasting on I-95. *IEEE Transactions on Intelligent Transportation Systems*, 20(8), 2987–2997. https://doi.org/10.1109/TITS.2018.2875765