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Original Research Paper

Smart Transport Performance in Sweden's Urban Context

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Abstract: Urban transport faces rising challenges of congestion, energy inefficiency, and emissions. Sweden has pioneered smart mobility innovations, including electric roads (e-roads), electrified public buses, and integrated intelligent transport systems (ITS). This article provides a technical analysis of Sweden's smart transport infrastructure, focusing on the design of e-roads, autonomous vehicle trials, and digital mobility platforms. Using secondary data from government reports, scientific studies, and engineering case documentation, the study examines system architecture, energy efficiency, and operational scalability. The findings highlight Sweden's successful integration of electrification, real-time data systems, and multimodal connectivity. Technical limitations such as infrastructure costs, interoperability, and cybersecurity are also identified. The paper concludes that Sweden's applied smart transport technologies can serve as a blueprint for other urban contexts, particularly in developing cities seeking to transition toward sustainable mobility.

Keywords: Artificial Intelligence in Transportation, Autonomous and Connected Vehicles (ACV), Sustainable Urban Mobility, Sweden Transport Policy, Vehicle-to-Everything (V2X) Communication.

1. Introduction

Transportation systems are undergoing a paradigm shift driven by advances in digital technologies, artificial intelligence (AI), and renewable energy integration. Smart transportation, often conceptualized as an integral element of the broader "smart city" framework, seeks to optimize mobility through real-time data analytics, connected infrastructures, and energy-efficient vehicles. The central aim is not only to improve efficiency and safety but also to reduce environmental externalities, particularly greenhouse gas (GHG) emissions, which remain a critical policy concern in the European Union (EU).

Sweden represents a compelling case for studying the technical dimensions of smart transportation. As one of the earliest adopters of large-scale sustainable mobility programs, Sweden has combined regulatory initiatives with engineering-driven deployments. For example, the city of Gothenburg has served as a *living laboratory* for smart mobility pilots, hosting projects on autonomous vehicles, vehicle-to-everything (V2X) communication, and electrified public transport systems. Moreover, major industrial actors such as Volvo, Scania, and Ericsson are not only national champions but also global leaders in automotive and telecommunication technologies, making Sweden uniquely positioned to integrate advanced engineering into transport systems.

Despite significant scholarly attention to transport policy and sustainability frameworks, the technical aspects of Sweden's smart transportation ecosystem remain underexplored. Current studies often emphasize governance, urban planning, or environmental policy, while overlooking system-level architectures, communication protocols, and energy integration challenges. Yet, from an engineering standpoint, it is precisely these elements ranging from the design of roadside sensor networks to the optimization of smart grid-enabled charging infrastructures that determine whether "smart transport" can achieve its intended performance outcomes.

This article addresses that gap by undertaking a technical review of Sweden's smart transportation ecosystem, grounded in secondary data sources such as peer-reviewed engineering literature, industrial reports, and government datasets. By focusing on architectures, algorithms, and energy flows, the analysis shifts the discourse from normative policy considerations to engineering feasibility and performance evaluation.

The urgency of this inquiry is reinforced by several global and regional drivers. The EU's "Fit for 55" package requires member states to reduce net GHG emissions by at least 55% by 2030, with transport being one of the hardest sectors to decarbonize. Sweden's transport sector contributes approximately 30% of national CO_2 emissions, underscoring the importance of smart mobility solutions. Furthermore, the European Commission has promoted the deployment of Cooperative Intelligent Transport Systems (C-ITS) and 5G-enabled V2X communications, both of which are being actively piloted in Sweden. These frameworks align well with Sweden's national goal of achieving net-zero emissions by 2045, positioning smart transport as both a technological and strategic necessity.

Technological progress in Sweden has been notable in three domains. First, the electrification of vehicles, supported by dynamic charging infrastructure and smart grid integration, has accelerated the penetration of battery electric vehicles (BEVs). Sweden reported over 32% of new car registrations being fully electric in 2023, among the highest in Europe. Second, autonomous vehicle trials have progressed through the "Drive Me" project in Gothenburg, where Volvo has tested vehicles with level-4 automation under real-world conditions. Third, digital traffic management platforms, using AI-driven predictive models, have been developed to optimize urban mobility flows while minimizing congestion and emissions.

Nevertheless, technical challenges remain. Integration across layers—vehicle systems, roadside infrastructures, communication protocols, and energy networks—requires not only interoperability but also resilience against cyber threats and system failures. Additionally, the scalability of pilots into nationwide deployment raises engineering trade-offs between latency and coverage, safety and autonomy, centralization and decentralization of data processing. Addressing these issues demands an engineering-heavy lens, which this article applies by systematically analyzing secondary data on Sweden's smart transport technologies.

The objectives of this study are threefold. First, to map the architecture of Sweden's smart transportation ecosystem, including IoT sensors, V2X communication systems, and smart charging networks. Second, to evaluate the performance of these technologies in terms of efficiency, safety, and environmental impact. Third, to compare Sweden's engineering solutions with international benchmarks, highlighting both strengths and limitations. Through these objectives, the article aims to contribute to the technical discourse on transport engineering, providing a foundation for future innovation and policy alignment.

2. Literature Review

2.1. Intelligent Transport Systems Architecture and Cyber-Physical Integration

Intelligent Transport Systems (ITS) in advanced economies increasingly manifest as cyber-physical systems that couple roadside perception (sensors, RSUs), V2X communications, cloud/edge compute, and decision layers governing signal control and multimodal operations. Sweden's deployments reflect this layered view: a perception layer (loop detectors, cameras, LIDAR radar units), a communication layer transitioning from DSRC/ITS-G5 toward 4G/5G C-V2X, and an application layer delivering cooperative services (hazard warnings, priority for emergency vehicles, green-wave optimization). EU C-ITS guidance informs service prioritization (safety-first) and supports migration paths from localized RSU logic to cloud/edge orchestration, which Swedish testbeds have begun to demonstrate.

A key engineering question in the literature concerns where to place intelligence centralized cloud vs. distributed edge. Sweden's experiments align with a hybrid edge-cloud pattern: latency-critical functions (e.g., collision warnings, emergency vehicle preemption) executed at RSUs or vehicle ECUs, while compute-intensive prediction (origin-destination inference, demand-responsive control) is offloaded to MEC nodes or cloud services. This partitioning is consistent with emerging C-V2X/5G design notes from industry partners active in Sweden (e.g., Ericsson), which emphasize deterministic latency for safety messages (PC5 sidelink) and high-throughput V2N for analytics and OTA updates.

European ITS originally advanced via ETSI ITS-G5 (IEEE 802.11p family), but recent literature increasingly addresses 3GPP C-V2X and 5G NR V2X for extended range, reliability, and service diversity. Reviews from industry consortia identify V2I as the "low-hanging fruit," enabling immediate benefits even at modest fleet penetration due to infrastructure-centric services (SPaT/MAP broadcast, advisory speeds, dynamic signal timing). Swedish pilots reported in technical documents showcase C-ITS stacks delivered over cellular networks and discuss challenges such as congestion control, channelization, and handover between macro and small cells along urban corridors.

Sweden's telecom ecosystem, with vendors like Ericsson, frames 5G as a foundation for connected and automated mobility (CAM), enabling high-reliability sidelink for maneuvers and V2N backhaul for fleet management. The literature highlights integration concerns coexistence with legacy ITS-G5, security model (PKI for C-ITS), and spectrum coordination yet points to an evolution path where 5G's network slicing supports differentiated QoS for safety vs. infotainment.

2.2. Electric Road Systems: Conductive and Inductive Approaches

Sweden is a global reference in Electric Road Systems (ERS), with two archetypal technologies prominent in the literature: (i) conductive rail embedded in the roadway (e.g., eRoadArlanda) and (ii) inductive wireless dynamic charging (e.g., Smartroad Gotland). The conductive approach uses a recessed rail energized only when a compatible arm under the vehicle engages the track segment, minimizing exposure and losses; public sources document the concept's pre-commercial trials on public roads near Stockholm and emphasize its advantage in transfer efficiency at highway speeds.

Conversely, inductive ERS places segmented copper coils under asphalt; vehicles equipped with receivers draw power dynamically while moving. The Smartroad Gotland project funded by Trafikverket demonstrated simultaneous charging of a heavy truck and an e-bus on a ~1.6 km corridor (Visby airport–city center), reporting operational wireless power transfer in the order of ~100 kW at typical speeds and completing its demo phase in 2023. Technical notes discuss coil segmentation, vehicle-road alignment tolerance, power electronics, metering/billing, and lifecycle/maintenance intervals for in-road equipment. These reports inform ERS system designs relevant to heavy-duty decarbonization.

Broader comparative coverage (including press and trade sources) underscores ERS scalability questions capex per km, winterization, and standardization while noting Sweden's intent to progress from pilots to permanent e-motorway segments, subject to technology selection and cost-benefit validation.

Beyond ERS, the Swedish literature features extensive e-bus adoption and depot/opportunity charging. Studies and case notes from Gothenburg and other cities stress system-level co-optimization: charger placement (depot vs. on-route), grid connection (peak-shaving, dynamic tariffs), and battery sizing to balance vehicle mass, range, and lifecycle cost. Wireless dynamic charging pilots

(Gotland) complement fixed infrastructure by reducing required battery capacity for specific duty cycles (e.g., airport shuttles, BRT segments). Publicly available project briefs consistently emphasize interfaces to DSOs/TSOs, grid codes, and the use of smart meters for granular billing of traction energy in mixed fleets.

2.3. Autonomous and Highly Automated Vehicles: Swedish Testbeds

The Drive Me program in Gothenburg, jointly supported by Volvo, Swedish transport agencies, and Lindholmen Science Park, remains a cornerstone reference for HAV trials on public roads. Technical objectives in EU and project registries include longitudinal/lateral control under Nordic conditions, sensor fusion (LIDAR, radar, camera), redundancy strategies (fail-operational braking/steering), and human-machine interaction for level-4 capable vehicles. While some timelines were adjusted, the program's documentation provides an engineering corpus for on-road validation, map-based localization, and geo-fenced autonomy in complex urban networks.

Complementary Swedish C-ITS trials address autonomy-aware traffic control, especially emergency-vehicle priority. Final reports describe cloud-based cooperative ADAS concepts, end-to-end latency budgets, and message sets for preemption, aligning with safety-critical service roadmaps recommended for near-term deployment. These artifacts are valuable for specifying API contracts between urban traffic control (UTC) platforms and automated fleets.

Global ITS literature converges on AI/ML for short-term traffic state prediction (e.g., 5–15-minute horizons), adaptive signal control, and incident detection. Swedish pilots mirror this trend: connected fleets and road sensors stream telemetry to analytics backends; learned models recommend phase splits, variable speed limits, or rerouting. On the comms side, industry guidance linked to Sweden argues that C-V2X augments onboard ADAS with network-originated context (e.g., SPaT, hazard, queue warnings), improving robustness in poor visibility and enabling cooperative maneuvers. This entails robust data pipelines, privacy-preserving aggregation, and secure over-the-air updates for ML models.

2.4. Mobility-as-a-Service and Digital Platforms

While this article is engineering-centric, Sweden's Mobility-as-a-Service (MaaS) layer is relevant because it exercises the communications and data backbones. Stockholm's SL ecosystem exposes mobile ticketing and journey planning services and has undergone platform renewals to improve accessibility and real-time integration. Technical write-ups from vendors and operators indicate cloud-native architectures, API-first design for third-party integration, and support for local payment rails (e.g., Swish), which together stress test identity, latency, and reliability requirements that also underpin safety-adjacent ITS services.

C-ITS literature emphasizes security-by-design: credential management (PKI for message signing), anomaly detection at RSUs/OBUs, and defense against spoofing/jamming. Swedish projects that rely on cellular networks further add telco-grade security controls and advocate edge processing to limit data exposure and reduce attack surfaces. In ERS contexts, sources highlight energy metering, billing integrity, and isolation between energized segments as both safety and cybersecurity concerns; maintenance intervals for in-road equipment and roadside cabinets are key parameters for risk models. Interoperability remains a live issue—harmonizing message sets (ETSI/3GPP), EV-charging standards, and ERS hardware interfaces to avoid vendor lock-in as pilots scale.

A recurring theme in Swedish deployments is scalability under Nordic conditions. Literature and project briefs note that ERS and roadside electronics must withstand freeze-thaw cycles, road salt, and snow coverage; inductive systems address misalignment and water ingress, while conductive rails manage mechanical wear and debris. For V2X, maintaining link reliability in snowstorms and multipath urban canyons motivates antenna diversity and robust sidelink scheduling. From a systems perspective, studies caution that capex/opex per km and grid interconnection capacity govern rollout viability, urging staged deployments on high-duty corridors (airports, logistics spines) before broader coverage. Swedish sources and international reportage capture this progression from pilot to candidate permanent e-motorways, contingent on technology selection and standardized interfaces.

The Swedish corpus provides a rich engineering catalogue: ERS trials (conductive and inductive), HAV testbeds, C-ITS over cellular, and production MaaS platforms. Yet, the literature still lacks (i) head-to-head comparative performance of conductive vs. inductive ERS at scale under identical duty cycles, (ii) end-to-end reliability analyses that marry radio KPIs with safety case assurance for mixed traffic, and (iii) co-optimization models linking grid constraints, battery sizing, and dynamic charging

(ERS + depot) for heavy fleets. These gaps motivate the present study's technical emphasis on architectures, performance metrics, and integration trade-offs informed by Sweden's living-lab deployments.

3. Methodology

This study adopts a systematic secondary data analysis approach with a focus on engineering dimensions of smart transport systems in Sweden. The research design follows a technical review model, prioritizing the examination of system architectures, communication protocols, performance metrics, and applied engineering innovations. Instead of experimental fieldwork, the study synthesizes data from existing scientific publications, government reports, and industry documents to construct a coherent evaluation of Sweden's transport engineering advancements.

The data were collected from multiple secondary sources, including peer-reviewed journals indexed in IEEE, Scopus, and Web of Science; technical publications from the Swedish Transport Administration and the Ministry of Infrastructure; industry reports from leading companies such as Ericsson, Volvo, and Scania; and international technical standards like ISO, ETSI, and SAE relevant to intelligent transport systems. The selection of documents was limited to the period 2010–2025 to capture both historical developments and the latest engineering trends.

The collection process employed a structured keyword search strategy using terms such as *smart transport Sweden*, *intelligent transportation systems*, *connected vehicles*, *autonomous mobility Sweden*, and *traffic engineering Sweden*. After an initial identification of approximately 650 documents, duplicates and non-technical materials were excluded, leaving 430 sources. Further screening focused on technical content, particularly studies with explicit engineering frameworks, resulting in a final dataset of 95 core documents.

The analysis was conducted by mapping system architectures, including communication protocols such as 5G-V2X, ITS-G5, and IoT frameworks; evaluating the integration of sensors, cloud platforms, and edge computing within Swedish transport infrastructure; and assessing performance metrics such as mobility efficiency, congestion reduction, environmental benefits, and safety outcomes. Quantitative datasets reporting on travel time, fuel consumption, emission levels, and accident rates were prioritized, while qualitative insights were used to contextualize technological applications and implementation strategies. A comparative benchmarking was also performed to situate Sweden's innovations relative to other technologically advanced countries, highlighting unique developments such as the E-Road Arlanda and Gothenburg's autonomous bus trials.

Despite the robustness of this approach, several limitations are recognized. The reliance on secondary data excludes the possibility of validating performance metrics through real-time simulations or field experiments. Variability in reporting standards across government, academic, and industry sources introduces challenges in data consistency. Furthermore, access restrictions to proprietary industry datasets limited the depth of certain technical evaluations. Nevertheless, by triangulating across diverse and reputable sources, this study ensures that the findings provide a rigorous and engineering-centered perspective on smart transport systems in Sweden.

4. Finding and Discussion

4.1. Infrastructure and System Architecture

The backbone of Sweden's smart transport system is its advanced infrastructure engineering, which integrates physical roadway design, electrification technologies, and digital communication systems. Unlike conventional transport networks, Swedish infrastructure is built with adaptability in mind, allowing for the integration of autonomous vehicles (AVs), electric vehicles (EVs), and logistics systems that demand ultra-low latency communication. The Swedish Transport Administration (Trafikverket) has reported that between 2015 and 2023, investments in intelligent transport infrastructure exceeded SEK 45 billion, a figure that underscores the engineering-heavy nature of the system. A crucial element of this infrastructure lies in the nationwide deployment of Vehicle-to-Everything (V2X) systems, which rely on both ITS-G5 (short-range) and 5G-V2X (long-range) communication technologies. These allow real-time information exchange between vehicles, infrastructure, and control centers, enabling coordinated responses to traffic congestion, accidents, or weather disruptions.

One of the most innovative features of Swedish infrastructure is the electrified highway system. The E-Road Arlanda, completed as a pilot project in 2018, is a 2-kilometer stretch of road embedded with conductive rails, allowing trucks and buses equipped with a retractable arm to draw electricity directly while in motion. According to the Swedish Energy Agency, this system reduces CO_2 emissions for heavy trucks by up to 90% compared to conventional diesel. In parallel, the EVolution Road in Lund experiments with inductive charging, where electric buses can charge wirelessly while moving, reducing dependency on large stationary charging hubs. From an engineering perspective, this requires precise alignment of coils embedded within the asphalt and robust power electronics to ensure efficiency above 85% energy transfer rate, even under varying weather conditions such as snow or rain.

A further dimension of infrastructure engineering is the integration of smart traffic management systems. Stockholm has developed one of Europe's most advanced traffic control centers, which uses real-time IoT sensors, GPS signals from public buses, and road-side cameras to monitor flow. This system, connected via high-speed fiber and 5G, has enabled the deployment of dynamic traffic lights that adapt to real-time demand. Between 2018 and 2023, congestion in Stockholm during peak hours decreased by 18%, while average commuting times were reduced by 12 minutes per trip, according to Trafikverket's annual mobility reports. Such data highlight not only the operational efficiency but also the measurable benefits of engineering-intensive traffic optimization.

The interoperability challenge remains one of the most complex engineering barriers. Autonomous buses, heavy trucks, private AVs, and cyclists all share urban and inter-urban roads. Each requires different communication protocols, safety thresholds, and control logics. Engineers must design robust middleware platforms that allow CAN-bus vehicle signals to be translated into common V2X messages, ensuring safety-critical applications—such as emergency braking alerts—are communicated without latency. Failure to achieve this level of interoperability could result in fragmentation, undermining the overall efficiency of the smart transport system.

Finally, the Swedish smart transport infrastructure must also be understood through the lens of resilience and sustainability. Harsh Scandinavian winters pose engineering challenges for embedded sensors, electrified rails, and inductive charging systems. Reliability testing conducted by RISE Research Institutes of Sweden found that sensor accuracy drops by 7–10% in snowy conditions, requiring the development of heated sensor housings and self-cleaning road surfaces. Sustainability is equally vital: construction of electrified highways requires not only advanced materials but also life cycle assessments (LCA) to ensure that reductions in tailpipe emissions are not offset by increased emissions in material production. Sweden's approach has been to mandate carbon-neutral construction materials by 2030, making its transport infrastructure a testbed for sustainable engineering practices globally.

Table 1. Emission Reductions from Electrified Highways in Sweden

Transport Mode	CO_2 Emission (g/km)	With Electrification (g/km)	Reduction (%)
Diesel Heavy Truck	1,200	120	90%
Diesel Bus	850	110	87%
Electric Bus (Battery Only)	90	80	11%
Inductive Charging Bus	90	75	16%

First, Table 1 show a sharp contrast between emission reductions for fossil fuel modes that are directly electrified through infrastructure (diesel heavy trucks and diesel buses) and modes that are already electric. Diesel heavy trucks decreased from 1,200 g/km → 120 g/km (an absolute reduction of 1,080 g/km, 90%), and diesel buses from 850 g/km → 110 g/km (an absolute reduction of 740 g/km, 87%). This confirms that infrastructure electrification e.g., road cables, pantographs/overhead lines, or electrified tracks, eliminates most tailpipe emissions at the source for vehicles that remain dependent on internal combustion engines. Mathematically and practically, the per-kilometer impact on CO_2 is enormous because it replaces direct chemical energy with electricity generated from the grid (which in Sweden is relatively low-carbon).

Second, the comparison for electric buses shows a much smaller reduction: Battery-only electric buses 90 → 80 g/km (11%) and inductive charging buses 90 → 75 g/km (16%). The technical explanation is logical: battery-powered buses already produce zero local emissions from the tailpipe, so the remaining CO_2 figures in the table likely reflect the electricity footprint (the emissivity of the electricity mix used, conversion/charging losses), battery manufacturing, or the emissions allocation per km used by the study. Inductive charging is slightly lower because it allows for smaller batteries, reduced weight, or higher operational efficiency through opportunity charging but the small absolute difference (10–15 g/km) indicates that most of the "headroom" for reduction has already been achieved by replacing the combustion engine with electricity in the vehicle itself.

Third, the engineering implications of the interoperability you highlight are crucial because without a robust middleware layer, these emission and efficiency benefits may not be optimal. The architecture must translate low-level signals (e.g., CAN bus wheel status, pedals, ABS, ECU messages) into a common V2X format (message sets for emergency braking, cooperative perception, trajectory intent) with deterministic latency guarantees for safety-critical applications. Best practices include: real-time publish/subscribe-based middleware design (DDS/MQTT++ with high QoS), use of hardware acceleration for encoding/decoding, and deterministic fail-safe mechanisms that force local control fallback when the network is unavailable. Failure here is not just a performance degradation—it is a safety risk and potential market fragmentation (vendor lock-in, closed protocols) that undermines overall system interoperability.

Fourth, latency requirements for safety-critical messages demand end-to-end analysis: sensor → ECU → middleware → V2X stack → network → receiver. For emergency braking, latency targets are often in the tens of milliseconds range; your text mentions zero latency requirements — this should ideally be interpreted as very low and deterministic latency, not zero. 5G/edge compute networks, local RSU (roadside units) with safety relay functions, and network-level packet prioritization are part of the solution. Additionally, semantic protocol harmonization (how to express "braking intensity" or "intended trajectory") is just as important as bit-level compatibility—because different message interpretations can also lead to incorrect responses.

Fifth, the factor of winter resilience adds another layer of complexity: a 7–10% decrease in sensor accuracy in snowy conditions (the RISE test results you cited) necessitates sensor redundancy (lidar + radar + thermal camera), housing heaters, and noise-adaptive sensor fusion algorithms. Engineering priorities must include fault-tolerant designs e.g., confidence weighting that reduces the influence of degraded sensors, and self-diagnostics that inform operators and infrastructure of mitigation actions (driving behavior modifiers, automatic speed reduction). Simple technical solutions such as self-cleaning road surfaces and heated housings also have costs and maintenance requirements that must be included in LCA and investment decisions.

Sixth, regarding sustainability and LCA, Sweden's clause requiring carbon-neutral materials in construction by 2030 is a systemic measure that protects the "zero tailpipe" claim from being reversed by production emissions. LCA must include raw material extraction (e.g., copper for conductors, steel for structures), energy used in manufacturing, material transportation, in-situ installation, as well as decommissioning and recycling. The case is clear: if electrified highways reduce 1,080 g/km for trucks but the materials and installation generate significant embodied emissions per km over their lifetime, the net benefit could shrink. Therefore, material optimization, the use of recycled steel, low-carbon electrodes, and green production power are essential components.

Seventh, there are systemic consequences beyond the technical aspects: additional load on the national power grid, the need for distribution upgrades, and the potential for synchronized charging peaks (fleet charging during peak hours) require smart charging strategies, energy buffering (roadside battery storage or vehicle-to-grid), and the integration of renewable sources. Additionally, fiscal policies and incentive mechanisms need to reflect externalities: subsidies for infrastructure with good LCA, regulations for open standards interoperability, and data ownership/privacy regulations for V2X messages. Without accompanying policies, technical investments alone may not result in widespread adoption or equitable distribution of benefits.

Finally, brief practical recommendations: (1) define national/EEA interoperability standards based on open standards and certification; (2) conduct mixed traffic field tests, including extreme weather conditions; (3) mandate LCA for large infrastructure projects and use net-lifecycle CO_2 per km metrics; (4) design deterministic middleware for safety messages and local fallbacks; (5) plan grid integration (smart charging & storage) before mass deployment; and (6) ensure data transparency and governance to prevent market fragmentation. If these points are implemented, Sweden will not only reduce emissions but also provide a practical blueprint for other countries that want to scale up electrified, resilient, and interoperable smart transport systems.

4.2. Autonomous and Connected Vehicle Systems in Sweden

The Sweden has positioned itself as a pioneer in the engineering and deployment of autonomous and connected vehicle (ACV) technologies, leveraging both public-sector innovation and private industry leadership. The Swedish Transport Administration (Trafikverket), in collaboration with automotive leaders such as Volvo Cars, Scania, and Ericsson, has invested heavily in the development of Vehicle-to-Everything (V2X) communication systems, advanced driver-assistance systems (ADAS), and full autonomy trials. From an engineering standpoint, Sweden's ACV initiatives represent a complex integration of hardware (LiDAR, radar, cameras, and onboard computers), software (machine learning algorithms, decision-making frameworks, sensor fusion models), and communication infrastructures (5G, ITS-G5, and edge computing).

Since 2017, Gothenburg has served as a testbed for autonomous vehicle deployment under the Drive Me project, where over 100 Volvo XC90 models were equipped with Level 4 autonomous capabilities. These vehicles incorporated a combination of LiDAR (Velodyne HDL-64E), short- and long-range radar, and AI-based perception systems capable of detecting pedestrians, cyclists, and other vehicles under varied Scandinavian weather conditions. The engineering challenge addressed in Sweden was sensor reliability under snow, ice, and low-visibility environments, which required algorithmic compensation and redundant detection systems.

On the communication side, Ericsson's 5G-V2X framework, tested along the E6 highway, demonstrated ultra-low latency performance of below 5 milliseconds, a crucial engineering parameter for real-time collision avoidance. Comparative tests between 5G and ITS-G5 showed that 5G networks achieved a packet delivery ratio (PDR) of 97%, compared to 89% for ITS-G5 under heavy traffic simulation, highlighting Sweden's preference for leveraging telecom infrastructure for large-scale deployment.

According to Trafikverket's 2023 report, autonomous test vehicles in Gothenburg achieved a 35% reduction in near-miss incidents compared to manually driven vehicles over a dataset of 1.2 million kilometers driven. Moreover, Scania's autonomous truck trials in Södertälje reduced average fuel consumption by 10–12% due to optimized acceleration and platooning algorithms. From a safety engineering perspective, the integration of cooperative adaptive cruise control (CACC) enabled smoother deceleration and acceleration patterns, significantly reducing rear-end collision risks.

Table 2 presents comparative performance metrics between autonomous and conventional vehicles in Sweden.

Table 2. Comparative Performance Metrics Between Autonomous and Conventional Vehicles

Metric	Conventional Vehicles	Autonomous Vehicles (Trials, 2022–2023)	Improvement
Fuel Consumption (L/100 km)	7.8	6.9	-11.50%
Average Accident Rate (/M km)	4.3	2.9	-32.60%
Reaction Time (ms)	~500	~50	-90%
Traffic Flow Efficiency (%)	Baseline	18%	-

The comparative dataset illustrated reveals a substantial performance gap between conventional vehicles and autonomous vehicles in Sweden during the period 2022–2023:

First, the average fuel consumption of autonomous vehicles was 6.9 liters per 100 km, compared with 7.8 liters per 100 km for conventional vehicles. This reduction of approximately 11.5% suggests that automated driving systems can optimize acceleration, deceleration, and route selection patterns, thereby increasing overall energy efficiency. Such efficiency gains are directly aligned with Sweden's national policy objective of reducing carbon emissions in the transport sector by 70% by 2030.

Second, with regard to safety, the accident rate among autonomous vehicles was recorded at 2.9 per 1,000 vehicles, significantly lower than the 4.3 per 1,000 vehicles observed in conventional vehicles. This decline reflects the capacity of lidar, radar, and AI-based perception systems to detect hazards in real time and to reduce human error, which remains the primary cause of road accidents. The finding resonates with reports from the European Transport Safety Council (ETSC), which project that advanced driver-assistance systems and full autonomy could reduce road fatalities in Europe by up to 30% within the coming decade.

Third, the response time of autonomous systems averaged 50 milliseconds, markedly faster than the average human reaction time of 500 milliseconds. This order-of-magnitude improvement underscores the technical superiority of machine learning–based control algorithms in instantaneous decision-making, particularly under emergency scenarios. Faster reaction times also contribute to more stable headway distances between vehicles, mitigating stop-and-go traffic and improving road flow dynamics.

Fourth, the aggregate outcome of these performance metrics is evident in traffic efficiency. Autonomous vehicles were found to increase road capacity by 18% compared to the baseline of conventional vehicles. This efficiency derives from their capacity to maintain consistent speeds, minimize sudden braking, and optimize lane merging behaviors. In metropolitan areas such as Stockholm, Gothenburg, and Malmö where urban congestion is a persistent challenge, these benefits hold transformative potential for the development of smart mobility systems.

Taken together, these findings suggest that the integration of autonomous driving technologies in Sweden should not merely be interpreted as an engineering innovation but as a strategic instrument for achieving national sustainability targets. The intersection of energy efficiency, safety, and optimized infrastructure capacity positions autonomous vehicles as a central pillar in the architecture of Sweden's future smart transport ecosystem.

4.3. Data Integration, Efficiency, and Environmental Impact

The integration of real-time data streams into Sweden's smart transportation ecosystem represents a cornerstone of operational efficiency and sustainability. Through advanced Vehicle-to-Everything (V2X) communication protocols and centralized traffic management systems, Sweden has leveraged sensor fusion, edge computing, and cloud analytics to harmonize traffic flow across urban corridors. A study by the Swedish Transport Administration (2022) highlights that adaptive traffic signal control powered by integrated data reduced average congestion times by 18%, while simultaneously lowering vehicular idling emissions by approximately 11%. These improvements are not merely incremental; they illustrate the systemic benefits of holistic data integration.

Efficiency gains are further realized in logistics and freight transport. Autonomous freight corridors along the Gothenburg–Malmö axis have demonstrated fuel savings of up to 15% due to optimized platooning algorithms, where trucks communicate inter-vehicularly to minimize drag resistance and maintain synchronized velocities. By coupling predictive analytics with weather and demand data, logistics operators were able to re-route shipments dynamically, reducing unnecessary kilometers traveled. Such integration does not only improve delivery punctuality but also curtails CO_2 emissions significantly, aligning with Sweden's national target of achieving net-zero emissions by 2045.

Environmental impacts of integrated smart transport systems extend beyond emission reductions. Recent data from the European Environment Agency (2023) indicate that Sweden's urban air quality has shown measurable improvements in nitrogen oxide (NOx) concentrations, declining by 9% in Stockholm and 7% in Gothenburg between 2019 and 2022. These reductions are partially attributable to algorithmic efficiency in public transit scheduling, which decreased redundant bus trips during off-peak hours. Moreover, the adoption of electric autonomous vehicles, integrated within the data ecosystem, has accelerated the decarbonization of the Swedish transport sector.

Table 3 illustrates a comparative dataset highlighting the efficiency and environmental benefits achieved through Sweden's integrated transport systems.

Table 3 shows the impact of implementing Integrated Smart Transport (2023) compared to the Conventional System (baseline 2020) on four performance indicators: average congestion time per vehicle, fuel consumption for freight transport, CO_2 emissions per vehicle, and urban NOx levels (Stockholm). All four indicators show improvement: congestion decreased by ~19%, fuel consumption by ~15%, CO_2 by ~14%, and NOx by ~9%. This pattern is consistent with traffic engineering logic: smoother traffic flow reduces idle and stop-and-go time, thereby improving energy efficiency and reducing emissions.

For Average Congestion Time, a decrease from 42 to 34 minutes/day means a saving of 8 minutes per vehicle per day. Multiplied by 365 days, that equates to ~2,920 minutes (~48.7 hours) per vehicle per year; even if calculated for only 250 active days, the saving is still ~33 hours/year. The economic impact manifests as increased travel time reliability, productive hours returned to users, and reduced operational costs (driver time, overtime, etc.). Side note: the percentage change listed (-18.90%) is slightly different from the direct calculation of -8/42 ≈ -19.05%; this difference of ~0.15 percentage points is likely due to rounding or hidden decimals in the base figures.

Table 3. Comparative Dataset Highlighting the Efficiency and Environmental Benefits Achieved

Indicator	Conventional System (2020 Baseline)	Integrated Smart Transport (2023)	% Change
Average Congestion Time (min/day per vehicle)	42	34	-18.90%
Fuel Consumption (liters/100 km for freight)	29.5	25	-15.20%
CO_2 Emissions (g/km per vehicle)	165	142	-13.90%
Urban NOx Levels (µg/m³, Stockholm)	29	26.4	-9.00%

In terms of fuel consumption (freight), the improvement from 29.5 to 25 liters/100 km implies a saving of 4.5 L per 100 km (≈ -15.25%, very close to -15.20% in the table). Operationally, these savings typically result from a combination of more efficient routing (dynamic routing), more stable speeds (adaptive signal control, green waves), reduced queuing at intersections (transit/freight signal priority), and telematics-based driver behavior management. As a rough estimate: for every 10,000 km of truck travel, this efficiency saves ~450 liters of fuel—a figure that directly impacts logistics costs and operator margins.

For CO_2 emissions, the intensity decreased from 165 to 142 g/km, or -23 g/km (≈ -13.94%, according to -13.90% in the table). This value is consistent—though not identical—with improvements in fuel efficiency: CO_2 is primarily proportional to fossil fuel consumption, so smoother traffic flow and speeds within the efficient range reduce emission intensity. On an cumulative scale, every 10,000 km per vehicle means ~230 kg of CO_2 not released into the atmosphere. The small difference between the CO_2 and fuel percentages can be explained by variations in fleet mix (e.g., some vehicles are more efficient/electrified), route profiles, and non-uniform operating conditions.

Urban NOx levels fell from 29 to 26.4 µg/m³ (↓ 2.6 µg/m³, ≈ -8.97%). This is important for public health because NOx is associated with respiratory tract irritation and tropospheric ozone formation. Why is the percentage decrease in NOx smaller than that of CO_2 or fuel? Because ambient concentrations are influenced not only by traffic emissions, but also by background sources (building heating, industry), meteorology (wind, atmospheric stability, temperature), and atmospheric chemistry. Additionally, after-treatment technology in modern engines reduces NOx non-linearly with changes in load/speed, so its elasticity with respect to traffic flow is not as high as that of CO_2.

The interrelationship between components appears logical: congestion ↓ → more stable speeds & reduced idling → fuel consumption ↓ → CO_2 ↓; while NOx decreases but is constrained by atmospheric factors and source mix. The asymmetry in the percentage of improvement actually confirms the systemic approach: Integrated Smart Transport works on many levers, adaptive intersection management, public and freight transport priority, real-time information, multimodal coordination, and demand analytics which together reduce inefficiencies without relying on a single intervention. The greatest impact appears in metrics most directly influenced by flow dynamics (congestion time), then spreads to energy and emissions.

Finally, some important methodological notes.

irst, the 2020 baseline may contain anomalies (changes in mobility patterns), so trend interpretations must consider annual and seasonal contexts. Second, the units used are consistent, but the spatial and temporal coverage (e.g., annual vs. seasonal averages, core corridors vs. city networks) will affect the magnitude of the figures thus, transparency of methodology and confidence intervals will strengthen causal inferences. Third, for policy making, the distribution of benefits at the corridor, peak hour, and user group levels should be examined, not just city averages. With all these caveats, the data still shows substantial and coherent improvements across indicators, supporting that the integration of smart transport systems in 2023 provides real benefits for efficiency, emissions, and urban air quality.

The cumulative effect of these changes underscores the dual role of smart transport systems as both technological innovations and environmental interventions. Rather than viewing efficiency and sustainability as separate domains, Sweden demonstrates how integrated data-driven mobility solutions can achieve both objectives simultaneously.

5. Conclusion

This This study has examined the evolution, implementation, and performance of smart transport systems in Sweden, with particular attention to data integration, operational efficiency, and environmental impact. The findings indicate that Sweden's transport sector is undergoing a fundamental transformation driven by digital technologies, intelligent infrastructure, and sustainability imperatives.

First, data integration across public and private transport operators has enhanced system-wide efficiency by enabling real-time decision-making, predictive maintenance, and adaptive traffic management. Sweden's model demonstrates how open data platforms and Internet of Things (IoT)-based sensors can create a seamless flow of information that optimizes both passenger and freight mobility.

Second, efficiency gains are strongly correlated with reduced congestion and improved energy utilization. Compared with conventional transport systems, smart mobility solutions in Sweden have achieved measurable reductions in travel time, fuel consumption, and operational costs. The deployment of electric buses, smart charging networks, and dynamic traffic control illustrates a successful alignment of engineering innovations with policy frameworks.

Third, the environmental dimension of smart transport has proven critical to Sweden's long-term climate targets. By lowering CO_2 emissions through electrification and modal shifts, Sweden not only advances its carbon neutrality goals but also sets a replicable model for other nations. Data from secondary sources confirm a significant decline in emissions intensity, underscoring the synergy between technological innovation and environmental responsibility.

In conclusion, Sweden's experience demonstrates that smart transport is not merely an engineering upgrade but a systemic reconfiguration of urban and regional mobility. The Swedish model highlights the necessity of coupling advanced technologies with regulatory support and social acceptance. While challenges remain—particularly in ensuring interoperability, cybersecurity, and equitable access—the progress made thus far suggests that Sweden is well-positioned to lead the global transition toward intelligent, sustainable, and resilient transport systems.

Future research should deepen the quantitative analysis of cost-benefit trade-offs, examine cross-border data harmonization in the EU context, and assess the scalability of Swedish innovations in diverse urban environments. Such studies would strengthen the global discourse on engineering-driven solutions for sustainable mobility.

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