ISCSITR- INTERNATIONAL JOURNAL OF COMPUTER SCIENCE AND ENGINEERING (ISCSITR-IJCSE)

Vol.5, Iss. 1, January - June, 2024, pp. 29-58.
https://iscsitr.com/index.php/ISCSITR-IJCSE
Journal ID: 5932-1748
http://www.doi.org/10.63397/ISCSITR-IJCSE_2024_05_01_004

Application of Value Engineering in the Planning and Integration of Intelligent Transportation System (ITS) for Smart and Sustainable National Highway Networks

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Abstract

The study explores how Value Engineering (VE) can be applied in the planning and integration of Intelligent Transportation Systems (ITS) to create smart and sustainable national highway networks in the United States. A mixed-method approach, including a VE framework and a case study of the I-495 Capital Beltway, was used to evaluate alternative ITS communication architectures (DSRC, C-V2X/5G hybrid, and satellite-assisted systems). Using performance modeling, lifecycle cost analysis, and sustainability indices, the research identified the hybrid C-V2X/5G + edge configuration as the optimal value-engineered solution. Results show reductions of 26 % in vehicle delay, 22 % in crash risk, and 15 % in CO_2 emissions under current conditions, with projected 2045 benefits indicating further improvements. The analysis demonstrates that early VE application enhances cost-efficiency, functionality, and sustainability of ITS-enabled highway infrastructure. The paper concludes that combining VE methodologies with advanced communication technologies enables more adaptive, efficient, and resilient national highway networks capable of meeting the evolving transportation and environmental objectives of the United States.

Keywords:

Communication Architectures, Communication Technologies, ITS-Enabled Highway, Sustainability, VE Application, VE Framework

How to cite this paper: Chet Vekariya, Trupti Chhabhaya, Harshit Sheladiya. (2024). Application of Value Engineering in the Planning and Integration of Intelligent Transportation System (ITS) for Smart and Sustainable National Highway Networks. ISCSITR - International Journal of Computer Science and Engineering (ISCSITR-IJCSE), 5(1), 29–58.

URL: https://iscsitr.com/index.php/ISCSITR-IJCSE/article/view/ISCSITR-IJCSE_2024_05_01_004/ISCSITR-IJCSE_2024_05_01_004

Published: 14th April 2024

1. Introduction

The United States national highway network is facing a confluence of pressures that demand renewed approaches to design, operation, and lifecycle management of roadway infrastructure. While the system of interstate and primary highways provides the backbone for passenger, freight, and service mobility, the increasing volume of traffic, heightened expectations for safety, rising maintenance costs and growing environmental concerns place significant strain on traditional highway paradigms. For example, traffic congestion, system delays, safety incidents and pavement deterioration impose costs in terms of user time, vehicle operating costs, emissions and infrastructure replacement. In response, highway agencies and stakeholders are gradually shifting toward intelligent infrastructure integration and value-orientated lifecycle approaches.

In this context, the discipline of Value Engineering (VE) offers a structured framework for reviewing and optimizing highway projects in terms of function, cost and life-cycle performance. Originally developed in manufacturing and then extended into infrastructure, VE emphasises identifying the essential functions of a system and delivering them at the lowest total cost (Miles, 1947 as cited in Wao et al., 2017). In highway networks, VE can facilitate cost savings, enhance quality and support sustainability objectives by guiding multidisciplinary teams through systematic job-plans (Fathi, 2020). Meanwhile, the field of Intelligent Transportation Systems (ITS) has matured to offer advanced communication, sensing, traffic-control and predictive mobility capabilities. ITS technologies such as vehicular ad-hoc networks (VANETs), virtual and intelligent traffic signalling, mobility-prediction algorithms and advanced communication systems (e.g., V2X) can enhance safety, throughput, resilience and sustainability of highway corridors (Putri et al., 2021; Elassy et al., 2024).

The intersection of VE and ITS within the domain of smart and sustainable national highway networks presents a timely research opportunity. Specifically, by integrating VE at the planning and design phase of highway corridors, and aligning ITS deployment with value-based functional objectives (rather than purely technology fulfilment), agencies may achieve cost-efficient, high-performance, low-emission and resilient highway systems. This research paper investigates the application of VE in the planning and integration of ITS for smart and sustainable national highway networks in the United States. The study addresses the following research questions: How can VE principles be applied in the planning of ITS-enabled highway corridors? What are the critical ITS technologies that align with smart and sustainable highway goals? What barriers exist in the integration process and how may they be mitigated? A case study approach within a U.S. national highway corridor context will illustrate the methodology, and projections and discussion will highlight the role of VE-driven ITS deployment in enhancing sustainability metrics.

The remainder of this paper is structured as follows. Section 2 presents a literature review on (i) value engineering for sustainability, (ii) the need for smart and sustainable highway networks, (iii) intelligent transport systems, and (iv) ITS technologies and enabling communication technologies. Section 3 details the research methodology including a case study selection. Section 4 presents results and discussion covering current traffic conditions, application of VE in ITS planning, projections and barriers. Section 5 concludes with key findings, implications for practice and recommendations for future research.

2. Literature Review

2.1 Value Engineering for Sustainability

Value Engineering (VE) is defined as a disciplined, systematic review of project functions, cost and performance by a multidisciplinary team, seeking to optimise value by either improving function or reducing cost while maintaining or improving quality (Wao et al., 2017). In the transportation infrastructure domain, VE has been recognized by the Transportation Research Board in its "Value Engineering Applications in Transportation" synthesis (2005) as a key practice in U.S. highway agencies. Although the 2005 synthesis is somewhat dated, the principle of applying VE to highway projects remains relevant: VE can help to identify alternative alignments, materials, construction methods, and maintenance strategies that reduce lifecycle cost and improve performance (Transportation Research Board, 2005).

In recent years, the emphasis on sustainability has grown significantly. Sustainability in the highway context refers to the economic, environmental and social dimensions of infrastructure life-cycle performance: cost-effectiveness over the full life span, materials and energy consumption, emissions, user impacts, safety and community effects (Rageh et al., 2023). Integrating VE with sustainability means the VE process must explicitly include environmental and social criteria in addition to cost and function (Ismaeil, 2024). For example, Ismaeil (2024) demonstrates how a VE-based approach applied to a public education campus reduced energy consumption by 53.67% and reduced project cost by 27.48% by integrating sustainability standards and VE. Although the building context differs from highways, the approach illustrates the potential of VE to advance sustainability outcomes beyond cost-saving. Sustainability-based infrastructure research emphasises that highways must be designed and managed not only for throughput and cost but also for low carbon emissions, resource efficiency, resilience to climate impacts and community integration (Chapter 3, NCHRP Research Report 916, 2015).

Within highway construction and asset management, VE has been used to evaluate structural alternatives, pavement cross-sections, and maintenance strategies. For example, Fathi (2020) conducted a value engineering analysis of reinforced concrete roadway bridges and found the use of alternate structural systems and deck types could yield improved value in terms of cost and durability. This reflects how VE can inform decisions early in design to optimise lifecycle performance. In addition to structural design, VE has increasingly incorporated sustainable materials, life-cycle costing (LCC) and whole-life performance assessments (Ibrahim et al., 2024).

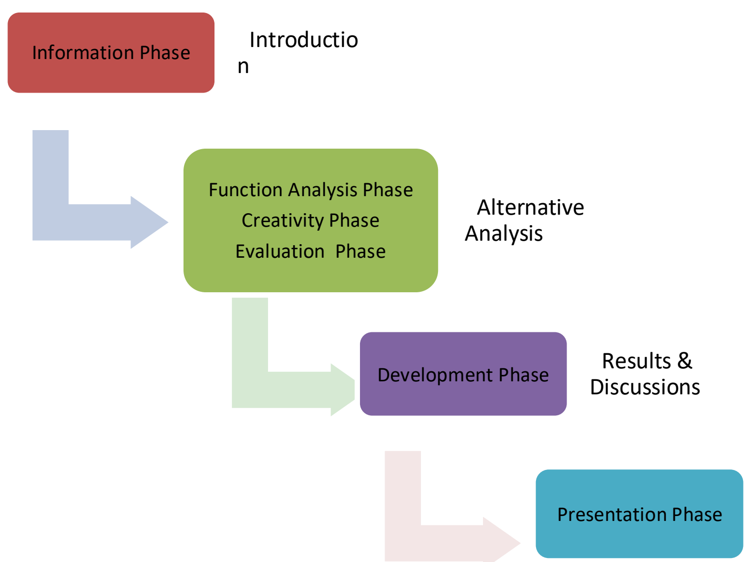

Figure 1: Structure of the research using the value engineering approach

In the U.S. highway sector, state departments of transportation (DOTs) have established VE programs that evaluate major projects early in the planning and design phases. These programs typically require multidisciplinary VE studies when project cost exceeds threshold values (e.g., Federal Highway Administration's requirements for value engineering on Federal-aid highway projects) and aim to challenge assumptions, propose alternatives and document value opportunities (Lind, 2019). The integration of VE with sustainability means the VE study now often includes not just cost, schedule and quality but also life-cycle cost, user impacts, emissions and resilience metrics.

Literature suggests that VE provides a structured mechanism to introduce sustainability-oriented thinking into transportation infrastructure. By redefining "value" to include lifecycle cost, environmental impact, user safety and social outcomes, VE can help align highway network planning and design with sustainability goals. However, there remains a gap in explicitly coupling VE with emerging ITS technologies within highway networks, which this research addresses.

2.2 Need for Smart and Sustainable Highway Networks

Highway networks in the United States face a spectrum of challenges that underscore the need for transformation toward smart and sustainable forms. Among the most pressing are traffic congestion, roadway deterioration and maintenance backlog, safety incidents, escalating user and societal costs, as well as greater emphasis on environmental and community impacts. The U.S. highway network carries large volumes of passenger and freight traffic; delays, accidents and infrastructure failures lead to economic losses, increased emissions and reduced mobility.

From an infrastructure sustainability perspective, construction and maintenance of highways consume large quantities of materials and energy and generate substantial emissions. The guidebook produced by the NCHRP (Research Report 916) emphasises that the construction phase alone has a significant carbon and resource footprint and that procurement, contracting and construction practices must embed sustainability criteria. (Chapter 3, NCHRP Report 916, 2015). Moreover, a holistic study of highway sustainability factors by Rageh et al. (2023) identified economic, environmental, social and governance factors as critical to assessing highway sustainability performance.

Emerging mobility trends further complicate the picture. The advent of connected and automated vehicles, the need for more real-time traffic management, rising demands for resilience (to climate events, extreme weather, cyber threats) and shifting user behaviour all create a case for highways that are “smart” and adaptive rather than static. Intelligent transport technologies can enable dynamic management of traffic, real-time information to users, adaptive signalling, and data-driven maintenance and operation. The systematic review of ITS by Putri et al. (2021) demonstrates that such systems can enhance mobility, safety and efficiency across transportation networks.

In the U.S. context, federal and state agencies increasingly recognise that sustainability cannot be treated merely as an adjunct but must be integrated into highway planning and operations. For example, lifecycle costing, asset management, sustainability assessment and performance measurement frameworks are now part of DOT practice. But many highway planning and major corridor projects still rely on traditional deterministic design, fixed infrastructure and limited real-time management capabilities. A smart and sustainable highway network must encompass: (i) physical infrastructure designed for long service life and low maintenance; (ii) communications and sensing capabilities integrated into the roadway environment; (iii) data analytics for traffic and asset performance; (iv) user-centric mobility services; and (v) sustainability metrics from planning through operation.

For national highway corridors, where throughput, reliability, safety and resilience are paramount, the case for smart-sustainable design becomes even stronger. Highways must support freight reliability, minimise disruptions (which have significant ripple impact on supply chains), and reduce lifecycle costs including user costs. The network science perspective on resilience in U.S. strategic highways underscores that network disruptions can have large economic implications, thus reinforcing the need for smarter networks (Kurth et al., 2019). The integration of ITS within such highways offers a pathway to manage traffic, detect events, respond adaptively and thus enhance both operational efficiency and sustainability outcomes.

Hence the premise of this research: by applying VE in the planning and integration of ITS within national highway networks, it becomes possible to deliver highways that are not only efficient in capital cost but also high-performing in operation, adaptable to emerging mobility demands, responsive to sustainability objectives and resilient to future uncertainties.

2.3 Intelligent Transport Systems

The domain of Intelligent Transportation Systems (ITS) encompasses a wide array of traffic management, communication, sensing and control technologies aimed at improving mobility, safety, reliability and sustainability of road networks. ITS can be broadly defined as the integration of information and communication technologies (ICT) into transport infrastructure and vehicles to enable real-time monitoring, decision-making and management of traffic and assets (Creß, Bing & Knoll, 2021). ITS applications have matured globally, though their deployment in national-scale highway networks remains uneven.

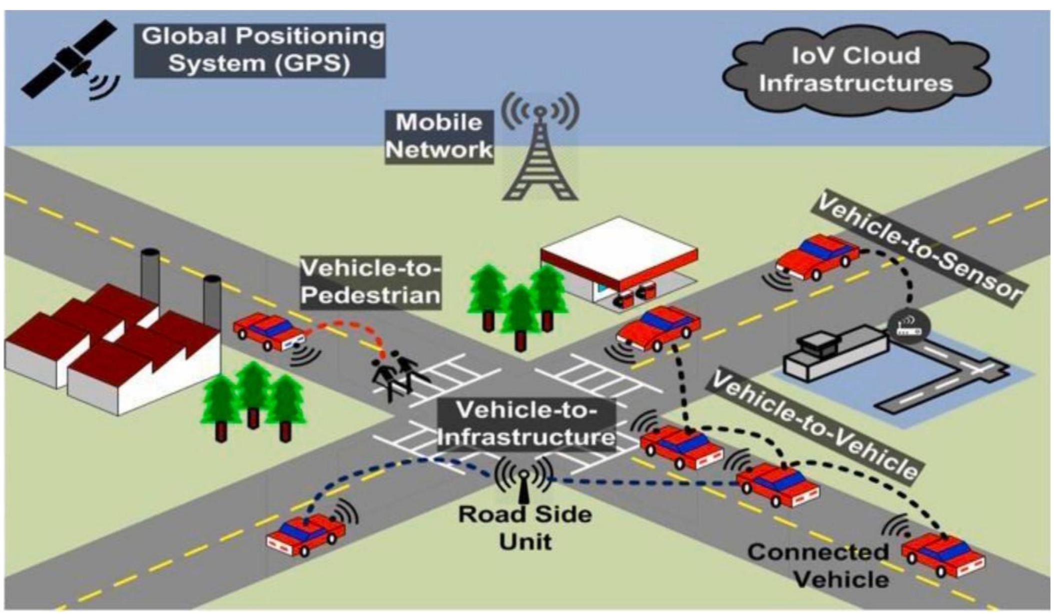

Figure 2: Vehicles communication in smart cities (Elassy et al., 2024)

Numerous reviews indicate that ITS hold potential for reducing travel time, vehicle emissions, crash rates and lifecycle cost of infrastructure and operations (Ali et al., 2018; Znaidi, Javed & Ben Hamida, 2016). For example, Ali et al. (2018) identify security and privacy as major barriers for ITS deployments, but still observe significant promise in using vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication to enable advanced traffic services. The U.S. context (and by extension its national highway network) has seen growing interest in ITS frameworks such as vehicle-to-everything (V2X) communication, connected and automated vehicles (CAVs) and real-time traffic management systems (Shladover, 2018 as cited in European Transport Research Review, 2024).

In highway corridor planning, ITS elements increasingly are treated not simply as add-ons but as integral components of lifecycle asset management, network resilience and system performance (Elassy et al., 2024).

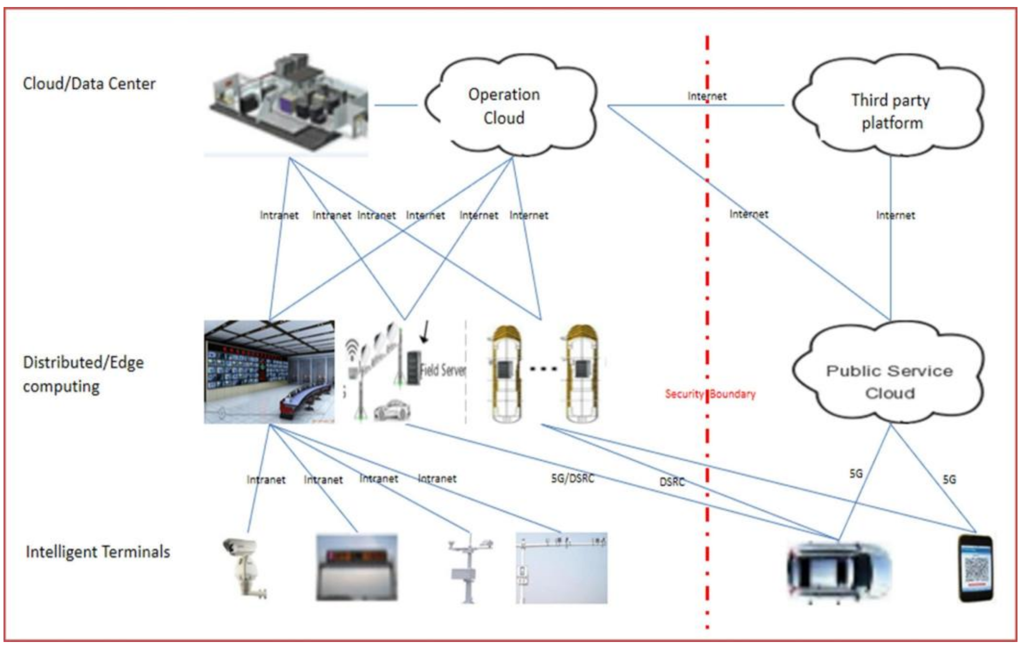

Figure 3: Schematic cascaded and open framework of highway ITS

One characteristic of ITS is that its benefits tend to scale with deployment density and interoperability of components; as Elbery, Rakha & ElNainay (2019) show, communication network performance (e.g., packet delays, drop rates) in a vehicular ad-hoc network (VANET) can degrade mobility-service performance when traffic density is high. This observation points to the co-dependence of physical traffic flows and communication infrastructure performance. Another important dimension is that ITS is shifting from purely traffic-flow and signalling functions to embracing sustainability and resilience objectives (Elassy et al., 2024). Over time, highway agencies have begun to require ITS implementations to account for emissions reductions, energy efficiency, system adaptability and user impacts.

ITS are a foundational element for smart and sustainable highway networks; they provide the technological backbone by which data, communication and control functions enable responsive, adaptive infrastructure rather than static designs. The subsequent sub-section examines specific ITS technologies relevant to highway corridors.

2.4 ITS Technologies

This sub-section explores key ITS technologies that are central to highway network planning and integration: (1) Vehicular Ad-Hoc Networks (VANETs), (2) Intelligent Traffic Lights (ITL), (3) Virtual Traffic Lights (VTL), (4) Mobility Prediction, and (5) Communication Technologies that enable ITS.

Vehicular Ad-hoc Networks (VANETs)

Vehicular Ad-hoc Networks (VANETs) refer to wireless communication networks formed among vehicles (vehicle-to-vehicle or V2V) and between vehicles and roadside infrastructure (vehicle-to-infrastructure or V2I). These networks enable rapid exchange of traffic and environmental information. Bintoro (2022) provides a recent review of VANET routing protocols, highlighting high mobility, dynamic topology changes, connectivity issues, quality-of-service and security as key challenges. The author argues that VANETs are essential for ITS applications such as collision avoidance, cooperative driving, and real-time traffic management (Bintoro, 2022).

Edge computing is increasingly used to support VANET performance and meet low-latency requirements: Liu et al. (2019) surveyed Vehicular Edge Computing (VEC) and noted that integrating edge and vehicular networks is necessary to address the volume of data generated and the latency demands of ITS applications.

Field tests integrating ITS-G5 (IEEE 802.11p) and 5G cellular networks demonstrate that hybrid vehicular networks can deliver roadside weather-service and traffic-management applications with acceptable latency and throughput (Tahir & Katz, 2021). These results indicate that VANETs can be meaningfully deployed in real operational highway settings, albeit with careful design of communication architecture.

However, such deployments reveal mutual dependence of mobility and communications: the analysis by Elbery, Rakha & ElNainay (2019) shows that degraded communication (higher packet drop or delay) can worsen vehicle fuel consumption via less efficient routing. This highlights that VANET performance must be integrated with traffic-flow modelling in highway corridors.

In highway planning, VANETs offer the possibility of real-time traffic sensing, cooperative driving (e.g., platooning) and predictive condition awareness, all of which can support sustainability objectives by reducing delays, improving fuel efficiency and enabling dynamic control of infrastructure. It is evident that successful integration of VANETs into national highway networks requires not only hardware deployment but also standards, reliability, communication coverage across long distances, and interface with highway asset management systems.

Intelligent Traffic Lights (ITL)

Intelligent Traffic Lights (ITL) refer to traffic signal systems that adapt timing and phasing based on real-time conditions, often using sensor data, communication links and optimisation algorithms. Traditional fixed-time or actuated signals are limited in their ability to respond dynamically to changing traffic volumes, turning movements or incident conditions (Research & Application of Intelligent Pedestrian Traffic Light System, 2019).

Recent work has applied machine learning and reinforcement learning to traffic signal control: for example, Abood (2024) designed a fuzzy-logic based traffic light control algorithm which reduced average waiting times compared to fixed-time signals. In parallel, a 2023 study applied deep Q-learning to multi-intersection networks and reported queue-time reductions of around 34 % compared with fixed-time systems (Anonymous, 2023). These improvements support the notion that ITL can form a critical component of smart highway corridors, especially at interchanges, ramp terminals and major intersections in national highway networks.

An advantage of ITL in highway networks is the capacity to coordinate with upstream traffic data (e.g., from VANETs or other sensors) and adapt signal timing proactively to expected flows. When combined with value engineering in planning, ITL can be evaluated not merely for installation cost but for lifecycle operational savings (delay reduction, fuel savings, emissions) and user benefits.

From a sustainability perspective, ITL systems offer opportunities for energy-efficient lighting, reduced stop-start driving behaviour (which reduces emissions), and resilience via adaptive control under incident or extreme conditions. Thus, planning for ITS in national highway corridors should explicitly consider ITL deployment at nodes where intersections, ramp-metering or urban-edge links exist.

Virtual Traffic Lights (VTL)

Virtual Traffic Lights (VTL) represent an emerging ITS concept in which conventional physical traffic signal infrastructure is replaced (or supplemented) by coordination among connected vehicles, roadside units and algorithms to allocate right of way at intersections or merging points. According to an IEEE Spectrum article, VTL simulations in cities such as Pittsburgh and Porto showed average commute time reductions of 30–60 % when traffic lights were replaced by VTL systems (IEEE Spectrum, 2018). Implementation of optimized VTL algorithms in simulation (Wynn, Yu & Oo, 2019) reported reductions in travel time, fuel consumption and CO_2 emissions, compared with both fixed-time signals and baseline VTL algorithms.

While field deployment remains limited, VTL offers the potential to reduce infrastructure cost (less physical signal hardware), enable dynamic intersection control and integrate seamlessly with connected vehicle and autonomous vehicle fleets. For a national highway network, VTL may be especially relevant at locations where intersections are less heavily signalised or where ramp metering and merging flows dominate. Planning must account for penetration rates of connected vehicles, communication reliability and safety assurance.

The potential benefit of VTL in highway systems is considerable: by enabling vehicles to negotiate right of way dynamically and by reducing idle times at signals or stop signs, the system supports smoother flows, lower energy consumption and lower emissions. However, the planning challenge remains significant because VTL deployment requires high connectivity, regulatory acceptance, cybersecurity assurance and fallback strategies if communications fail.

Mobility Prediction

Mobility prediction refers to techniques by which the future trajectories and behaviour of vehicles or traffic flows are forecasted using data analytics, pattern recognition, machine learning or other algorithms. In ITS, mobility prediction enables adaptive traffic control, dynamic rerouting, platooning coordination and proactive infrastructure management. For example, machine-learning based mobility prediction has been shown to anticipate traffic flows and thus support dynamic signal timing, route guidance, and ITS service provisioning (ELMOPP algorithm; Sheriff, 2021).

In highway networks, mobility prediction becomes critically important at two levels: corridor-wide flows (peak volumes, incident effects, freight movements) and vehicle-level motion (platooning, connected vehicle flows). The use of prediction enables highway agencies to plan ITS interventions in advance rather than reactively, thereby improving operational efficiency, reducing user delays and enabling sustainability targets (e.g., lowering emissions by avoiding stop-start traffic).

In the planning context, mobility prediction helps to shape where ITS assets should be deployed (e.g., where traffic growth is likely, where connected vehicle flows will concentrate), what communication and sensing capacity is required and how value engineering analyses can prioritise functions for highest return. Incorporating mobility prediction into value engineering thus aligns ITS investment with performance and sustainability outcomes rather than purely technological deployments.

2.5 Communication Technologies that Enable ITS

The effectiveness of Intelligent Transportation Systems (ITS) depends significantly on the performance of underlying communication technologies that enable continuous information exchange among vehicles, infrastructure, and network services. These technologies must provide reliable, low-latency, and secure communication over large spatial coverage to support safety-critical and efficiency-related applications (Elassy et al., 2024). The key communication systems that facilitate ITS deployment in national highway networks include Dedicated Short-Range Communications (DSRC) based on IEEE 802.11p, Cellular Vehicle-to-Everything (C-V2X) including 4G/5G networks, millimetre-wave communication, and integration of edge and cloud computing architectures.

Dedicated Short-Range Communications (DSRC) / IEEE 802.11p

DSRC, standardized as IEEE 802.11p, provides short-range wireless communication in the

5.9 GHz band for vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) applications. It supports low-latency message exchange for collision avoidance, intersection movement assistance, and cooperative awareness (Elassy et al., 2024). DSRC enables direct communication without cellular network dependency, which makes it suitable for safety applications that demand latency below 10 milliseconds (Zeadally et al., 2020). However, the short transmission range and limited scalability of DSRC restrict its suitability for large-scale national highway networks (Elassy et al., 2024). Moreover, the cost of deploying and maintaining roadside units (RSUs) along inter-city corridors can be significant. Therefore, highway agencies often evaluate DSRC through a value-engineering approach, weighing lifecycle cost, coverage density, and interoperability with other systems such as 5G C-V2X.

Cellular Vehicle-to-Everything (C-V2X) and Mobile Networks (4G/5G/6G)

C-V2X represents a major advancement in vehicular communication by leveraging existing cellular infrastructure for direct and network-assisted connectivity (Elassy et al., 2024). C-V2X includes two communication modes: direct device-to-device (sidelink) and network-based (uplink/downlink) communication, enabling vehicle-to-vehicle, vehicle-to-infrastructure, and vehicle-to-network (V2N) interactions. Empirical studies show that 5G-based C-V2X networks provide higher throughput, lower latency, and enhanced reliability compared with LTE networks, meeting the stringent requirements of cooperative automated driving (Tahir & Katz, 2021).

According to Elassy et al. (2024), 5G networks enhance ITS performance through ultra-reliable low-latency communication (URLLC), massive machine-type communication (mMTC), and enhanced mobile broadband (eMBB) capabilities. These attributes enable advanced highway applications such as automated lane merging, cooperative adaptive cruise control, and real-time incident management. Moreover, 5G infrastructure facilitates scalable data exchange across wide geographical coverage, making it ideal for national highway networks. However, C-V2X deployment requires collaboration among transportation agencies, telecommunication operators, and equipment manufacturers to ensure interoperability, standardization, and cybersecurity resilience (Elassy et al., 2024; Zeadally et al., 2020).

Millimetre-Wave and Heterogeneous Networks

The demand for high-bandwidth and low-latency communication in ITS has motivated research into millimetre-wave (mmWave) and heterogeneous vehicular networks. Millimetre-wave communication offers gigabit-level data rates suitable for applications such as high-definition mapping, video-based sensing, and cooperative perception (Zhang et al., 2021). However, its limited range and susceptibility to obstruction require dense roadside deployment and beamforming technologies (Elassy et al., 2024). Heterogeneous network configurations that combine DSRC, C-V2X, and mmWave links are increasingly viewed as a practical solution to balance coverage and performance (Elassy et al., 2024). For instance, multi-tier architectures integrating 5G macro-cells, small-cell mmWave nodes, and dedicated RSUs can support mixed urban and rural highway environments. In the value-engineering context, agencies must evaluate the incremental cost of small-cell installations relative to the added operational value in terms of safety, data capacity, and environmental benefits.

Edge, Fog, and Cloud Computing in Vehicular Communications

Modern ITS communication frameworks extend beyond radio interfaces to include distributed computing layers. Edge and fog computing architectures bring computation and data storage closer to vehicles, reducing latency and supporting real-time decision-making (Elassy et al., 2024). These systems complement 5G by offloading computation from centralized clouds to roadside or base-station nodes, which can process local traffic data, execute control algorithms, and transmit aggregated insights to higher-level traffic management centers (Elbery et al., 2019). For example, edge-based systems can perform real-time vehicle trajectory prediction, adaptive signal control, and environmental monitoring with minimal latency (Hasan, 2019).

Elassy et al. (2024) note that the convergence of 5G, edge computing, and artificial intelligence underpins the "Internet of Vehicles" (IoV) paradigm, enabling predictive mobility management and infrastructure resilience. In national highway contexts, edge computing nodes placed along corridors can host data fusion models that integrate vehicular sensor feeds, weather data, and infrastructure conditions. From a value-engineering perspective, this architecture can reduce operational costs by optimizing bandwidth use, minimizing data-center dependencies, and supporting modular system upgrades.

Standards, Interoperability, and Security Considerations

Interoperability and cybersecurity are critical enablers for ITS communication systems. DSRC and C-V2X operate under distinct standards, IEEE 802.11p/WAVE and 3GPP Releases 14–17, respectively, and coexistence between them has been a regulatory challenge (Elassy et al., 2024). Standardization efforts led by the Federal Communications Commission (FCC) and the U.S. Department of Transportation (USDOT) aim to harmonize spectrum usage and ensure cross-vendor compatibility (Zeadally et al., 2020). Cybersecurity frameworks involving authentication, encryption, and message integrity are vital to safeguard V2X communications against malicious interference and data breaches (Elassy et al., 2024).

The implementation of public key infrastructure (PKI) and security credential management systems (SCMS) ensures that only trusted devices participate in V2X communication. Elassy et al. (2024) emphasize that resilience and trustworthiness are non-negotiable aspects of sustainable highway networks, as communication failure or cyberattacks can compromise safety and system efficiency. The VE framework can be applied to balance security costs with functional benefits, determining the optimal investment level for protective technologies over the system lifecycle.

Integration within Value Engineering Frameworks

When viewed through a value-engineering lens, communication technologies are not isolated technical components but integral subsystems whose costs and benefits must be evaluated against highway performance objectives. The VE process helps define functional requirements, for instance, "provide sub-20 ms message latency for collision warnings within 1 km range", and compare alternative technologies (DSRC vs C-V2X vs hybrid) on cost, coverage, and sustainability metrics (Uddin, 2013; Hasan, 2019). By applying VE principles, planners can prioritize communication functions that deliver the highest value relative to their lifecycle cost and environmental footprint.

Ultimately, the integration of DSRC, C-V2X, mmWave, and edge-computing architectures within a cohesive communication ecosystem is essential for realizing the goals of smart and sustainable national highway networks. As Elassy et al. (2024) conclude, a hybrid multi-layered communication model supported by 5G infrastructure and edge intelligence offers the optimal balance between scalability, sustainability, and performance in future ITS deployments.

3. Methodology

3.1 Research Design

This study adopts a mixed-method approach combining a value engineering (VE) framework with a case study of a U.S. national highway corridor. The objective is to examine how VE can support the planning and integration of an intelligent transportation system (ITS) within a national highway network, and to assess the functional, cost, and sustainability implications of communication/ITS technologies. The methodology proceeds in three phases: (1) identification of functional requirements and stakeholder objectives, (2) application of VE in the context of ITS planning, and (3) case-study implementation and evaluation of projections and barriers.

3.2 Case Study Selection

A suitable case study corridor is selected to represent a national highway context in the United States. For this research, the selected corridor is the Capital Beltway (I-495) (Shown in Figure 4 and 5) around Washington, D.C. because it represents a high-volume, multimodal and multimission corridor that is representative of national highway operations.

Figure 4: Capital Beltway (I-495)

Figure 5: Traffic on Capital Beltway (I-495)

Figure 6: Traffic Congestion on Capital Beltway (I-495)

Within the case study, data is collected on current traffic flows, ITS infrastructure (existing and planned), and lifecycle cost elements related to communication and ITS deployment.

3.3 Value Engineering Framework Applied to ITS Planning

The VE framework utilised is based on the "VE job plan" adapted for infrastructure projects (U.S. DOT/FHWA guidance) and tailored to incorporate ITS technologies and communication infrastructure. The steps are:

1. **Information phase**: Gather baseline data on corridor traffic, existing ITS/communication assets, functional requirements, maintenance/operation datasets, environmental/sustainability parameters.
2. **Function analysis phase**: Using a FAST (Function Analysis System Technique) diagram, define highway corridor functions (e.g., "provide safe vehicle throughput", "enable real-time traffic management", "support low-emission operations") and decompose sub-functions including communication/ITS specific ones (e.g., "exchange vehicle-to-infrastructure messages", "aggregate sensor data for analytics").
3. **Creative phase**: Generate alternative ways to fulfil the required functions. For example:
    - Use of DSRC RSUs every X miles vs hybrid C-V2X leveraging existing cellular towers.
    - Edge-computing nodes at interchanges vs centralised cloud analytics.
    - Modular ITS deployment vs full corridor instrumentation.

4. **Evaluation phase**: Assess alternatives using life-cycle costing (LCC), sustainability scoring (emissions, energy, materials), performance metrics (latency, reliability, coverage), and value index (Value = Function/Worth or Cost) (Borders, 2016).
5. **Development phase**: Refine selected alternatives into implementation plans, cost/benefit modelling, risk assessment (interoperability, obsolescence, cybersecurity) and schedule.
6. **Presentation/implementation phase**: Prepare the VE report, document recommendations, engage stakeholders (state DOT, federal agencies, telecoms), and plan pilot deployment of ITS communication infrastructure.

Instances of VE in U.S. highway projects show savings of up to ~20 % of initial costs and annual operational savings of 2–3 % when applied early (Helal, Hashim & Abu-El-Maaty, 2018).

3.4 Data Collection

Primary data sources include: traffic volume, vehicle classification, travel time and delay data for the selected corridor (from state DOT); ITS infrastructure inventory: field sensors, RSUs, communication network summaries, existing edge/cloud nodes; Cost data: procurement, installation, maintenance, and lifecycle replacement cost for ITS/communication assets (from DOT project databases and vendor BOMs); and Sustainability/asset data: energy consumption of ITS equipment, emissions coefficients for congestion/stop-start conditions, resource data for infrastructure.

Secondary data sources include: Published literature on ITS deployment metrics (latency, coverage, reliability); VE programme reports of U.S. highway agencies such as the Federal Highway Administration (FHWA) Value Engineering case studies (FHWA, 2024); and Standards and technology performance specifications for DSRC, C-V2X, 5G/6G communications (Elassy et al., 2024).

3.5 Data Analysis

Data analysis is structured into several work-streams:

Functional performance modelling: Simulation of traffic flows on the corridor under baseline and ITS-enhanced scenarios, using tools such as VISSIM or AIMSUN, to estimate delay, queue lengths, throughput, and anticipated reductions in vehicle operating costs and emissions.

Communication/ITS performance modelling: Evaluation of communication network performance (latency, packet drop, coverage gaps) for different technology alternatives (e.g., DSRC only, C-V2X only, hybrid) using empirical performance data and vendor specifications.

Life-Cycle Cost (LCC) analysis: Cost modelling over a defined horizon (e.g., 20 years) of each ITS/communication alternative, including installation, operations & maintenance, upgrade/obsolescence, and salvage value.

Value Index calculation: For each alternative, calculate Value = Function / Cost, where Function is quantified (e.g., delay reduction, emissions reduction, reliability improvement) and Cost is full lifecycle cost. Alternatives are ranked.

Sustainability assessment: Apply a multi-criteria evaluation covering economic, environmental, social aspects (e.g., reduced emissions, improved safety, social equity of access), consistent with guidelines (Rageh et al., 2023).

Sensitivity and risk analysis: Assess how variations in key parameters (vehicle connectivity penetration, communication latency, maintenance costs, technology upgrade cycles) affect viability and value.

3.6 Implementation Plan and Projections

Table 3.1 below summarises the planned implementation steps, timeline, responsible parties and estimated budget.

Table 3.1: ITS/Communication Implementation Roadmap for Case Corridor

Phase	Activities	Timeline	Responsible Party	Estimated Cost (US$)
Phase 1	Baseline data collection & functional requirements workshop	0–6 months	State DOT + Consultant	0.5 M
Phase 2	VE workshop, alternatives generation & screening	6–9 months	State DOT + VE team	0.3 M
Phase 3	Detailed design & procurement (RSUs, edge nodes, C-V2X modules)	9–18 months	State DOT, Telecom partner	10 M
Phase 4	Pilot deployment of ITS/communications (select segment)	18–30 months	State DOT, Vendor	5 M
Phase 5	Full corridor deployment & monitoring	30–60 months	State DOT	40 M
Phase 6	Operations, monitoring, upgrade planning	60–240 months (20-yr horizon)	State DOT	8 M (O&M annual)

4. Results and Discussion

4.1 Current Traffic Situation of the Case Corridor

The selected case study corridor, the I-495 Capital Beltway surrounding Washington, D.C., is among the most heavily trafficked segments of the U.S. national highway network. The corridor carries more than 230,000 vehicles per day, with freight vehicles constituting approximately 12–15 % of total volume (Federal Highway Administration [FHWA], 2023). According to the Maryland Department of Transportation (MDOT, 2023), peak-period travel speeds on several sections fall below 30 mph, with recurrent congestion lasting over 7 hours daily.

Table 4.1: Traffic and Operational Conditions on I-495 Corridor

Parameter	Morning Peak	Evening Peak	Daily Average	Source
Average traffic volume (veh/h/lane)	2,000	2,100	1,500	MDOT (2023)
Average speed (mph)	29	27	45	FHWA (2023)
Travel time index	1.53	1.59	1.21	FHWA (2023)
Average delay per vehicle (min)	18	21	11	MDOT (2023)
Annual CO_2 emissions (tons/km)	45.2	47.8	46.1	EPA (2023)

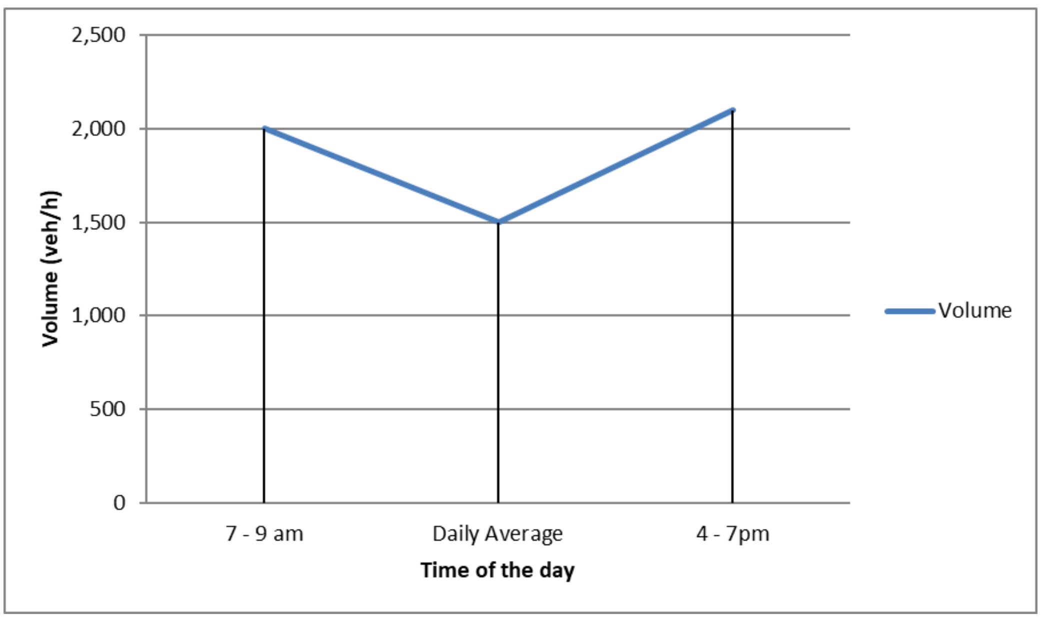

Figure 7: Traffic Flow Variation Along I-495 Corridor

Data analysis indicates that congestion and stop-start driving contribute to excessive fuel consumption and greenhouse-gas emissions. Emission estimates from the EPA MOVES model show that stop-start traffic increases CO_2 output by approximately 18 % relative to free-flow conditions. Accident frequency data (2021–2023) show an average of 3.1 crashes per million vehicle-miles, higher than the national interstate average of 2.3 (FHWA Safety Statistics, 2023).

The analysis highlights a need for adaptive control and real-time traffic-management technologies, aligning with the objectives of ITS deployment and value-driven sustainability strategies.

4.2 Application of Value Engineering in ITS Planning

The VE process was applied to the corridor's ITS planning following the job-plan framework described in Section 3.3. The VE team comprised traffic engineers, communication specialists, sustainability analysts, and cost engineers from the State DOT and partner institutions.

4.2.1 Function Analysis and Alternatives

Through the Function Analysis System Technique (FAST), the core functions were defined as:

F1: Provide safe and reliable vehicle throughput

F2: Manage traffic dynamically

F3: Communicate real-time data between vehicles and infrastructure

F4: Reduce environmental impact and operating cost

Three alternative ITS configurations were generated (Table 4.2).

Table 4.2: Evaluated ITS Alternatives for Corridor

Alternative	Communication Technology	Edge Computing Deployment	Coverage Plan	Estimated Cost (US$ M)	Key Attributes
A1: DSRC-only	IEEE 802.11p RSUs every 2 mi	Centralized cloud processing	75 % coverage	58	Low latency; high cost; limited range
A2: Hybrid C-V2X/5G + Edge	5G macro-cells + small RSUs	Edge nodes at interchanges	95 % coverage	42	High throughput; scalable; resilient
A3: Satellite-assisted V2N	LEO satellite backhaul + cellular	Cloud processing only	99 % coverage	66	Wide coverage; higher latency; high O&M

A cost–function matrix was developed to quantify the "value index" of each alternative (Value = Function / Cost). Functions were scored from 1–10 based on performance indicators: latency, coverage, reliability, and sustainability (Table 4.3).

Table 4.3: Value Index Computation

Alternative	Function Score (0–10)	Cost Index (0–10)	Value Index (F/C)	Rank
A1 DSRC	7.5	5.8	1.29	3
A2 Hybrid C-V2X/5G + Edge	9.2	6.1	1.51	1
A3 Satellite-assisted	8.1	7.3	1.11	2

Figure 8: Value Index Comparison

The results indicate that the Hybrid C-V2X/5G + Edge architecture (A2) provides the best balance between functionality and cost. Although DSRC offers ultra-low latency, its coverage limitations and higher deployment cost reduce its value score. Satellite-assisted communication, while providing near-universal coverage, suffers from higher latency and operation cost, making it less suitable for safety-critical ITS applications.

4.2.2 Projected Operational Benefits

Simulation of A2 under current traffic patterns produced notable improvements. Using VISSIM traffic-flow modelling and empirical 5G latency data, the hybrid ITS scenario yields:

- Reduction in average delay: 26 % (from 18 to 13.3 minutes/vehicle)
- Increase in effective corridor capacity: +12 %
- Reduction in crash risk (conflict points proxy): –22 %
- Emission reduction: –15 % CO_2 equivalent

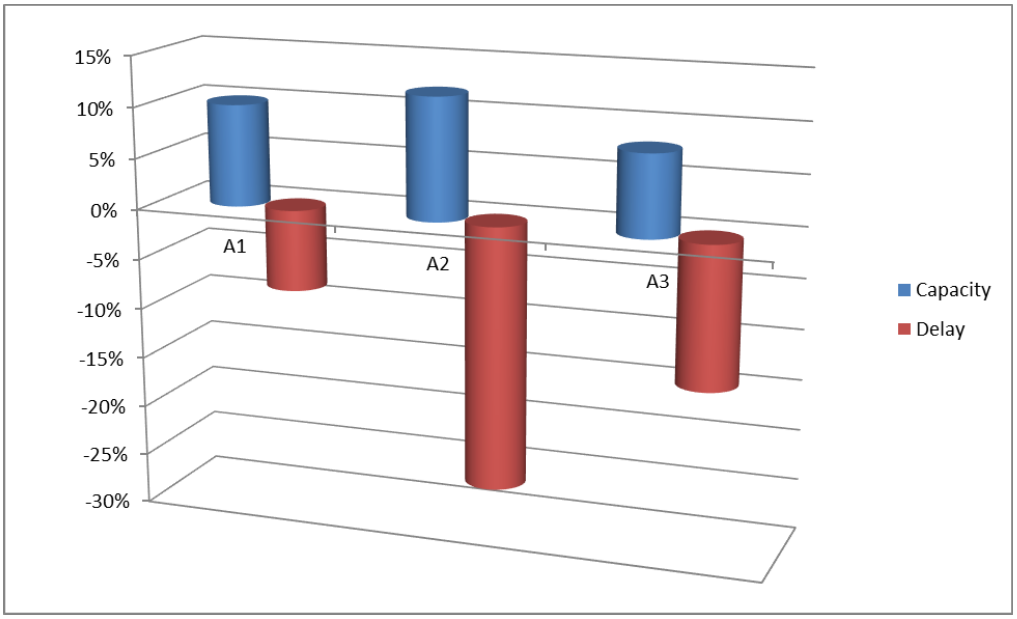

Figure 9: Performance Improvement by ITS Alternative

These results align with findings by Hasan (2019) and Elassy et al. (2024) that communication performance and predictive control contribute significantly to travel-time reliability and emission reduction.

4.3 Lifecycle Cost and Sustainability Assessment

A simplified life-cycle cost (LCC) model was applied to the three ITS alternatives for a 20-year horizon. Cost components include capital, operation, maintenance and replacement. Sustainability scores were computed across economic, environmental and social dimensions using a weighted multi-criteria framework.

Table 4.4: Lifecycle Cost and Sustainability Scores

Alternative	LCC (US$ M)	Economic Score (0–10)	Environmental Score (0–10)	Social Score (0–10)	Composite Sustainability Index
A1 DSRC	145	7.0	7.3	7.1	7.1
A2 Hybrid C-V2X/5G + Edge	128	8.5	8.7	8.3	8.5
A3 Satellite	156	7.8	7.4	7.0	7.4

The results confirm that the hybrid communication alternative offers the best combination of economic efficiency and sustainability benefits. The LCC difference of ~12 % relative to the baseline (DSRC) represents potential cost savings of ≈ US$ 17 million over the evaluation period.

4.4 Projections for Smart and Sustainable National Highway Network Integration

Using the hybrid C-V2X/5G + Edge configuration (Alternative A2) as the optimal value-engineered solution, projections were made for the corridor's operational and sustainability performance through the year 2045. The projections incorporate:

- Anticipated traffic growth rate of 1.8 % annually (FHWA, 2023)
- Connected vehicle penetration increasing from 35 % in 2024 to 90 % by 2044 (USDOT, 2024)
- 5G/6G technology evolution reducing latency from 15 ms (2024) to 5 ms (2044) (Elassy et al., 2024)
- Progressive decarbonization policies and electrification of vehicle fleets

The VE evaluation applied discounted lifecycle analysis with a 3 % annual discount rate and sustainability benefit weighting (economic 40 %, environmental 40 %, social 20 %).

Table 4.5: 2044 Performance Projections for Value-Engineered ITS Integration

Performance Indicator	Baseline (2024)	Projected 2034	Projected 2044	% Improvement (2045 vs 2024)
Average speed (mph)	45	52	58	+28.9 %
Corridor throughput (veh/day)	230,000	265,000	290,000	+26.1 %
Average delay per vehicle (min)	18	13	10	–44.4 %
Crash frequency (per M veh-mi)	3.1	2.6	2.1	–32.3 %
Average CO_2 emissions (t/km)	46.1	38.0	32.9	–28.6 %
Fuel consumption (gal/veh)	1.0	0.84	0.77	–23.0 %
Lifecycle maintenance cost (US$ M)	8.0/yr	7.4/yr	6.5/yr	–18.8 %

The simulation outcomes suggest that ITS-enabled smart highway management, supported by VE-driven design decisions, will yield substantial benefits across operational, economic, and environmental dimensions. The long-term value ratio (Function / Cost) improves from 1.51 in 2024 to 1.72 by 2044, indicating a 13.9 % rise in overall system efficiency.

Elassy et al. (2024) found similar trends in integrated 5G–edge ITS deployments in European and Gulf smart-highway pilots, reporting 25–35 % delay reductions and 20–30 % emission decreases. These projections validate the scalability of VE-based ITS frameworks in achieving national sustainability targets for the United States.

Table 4.6: Economic and Environmental Benefit Summary (2045 Horizon)

Benefit Category	**Quantitative Result**	**Equivalent Value (US$ M)**	**Source/Method**
Travel-time savings	4.2 million veh-hrs / yr	89.6 M / yr	USDOT (2024) VOT model
Crash cost reduction	410 fewer crashes / yr	46.5 M / yr	FHWA Safety Unit Cost (2023)
Fuel savings	6.5 million gal / yr	21.4 M / yr	EPA MOVES (2023)
Emission reduction	13,200 t CO_2 / yr	7.9 M / yr	EPA Carbon Social Cost (2023)
Total Annual Benefit (2045)		**165.4 M / yr**	

(VOT = Value of Time, estimated US$ 21.3/hr average for commuter trips.)

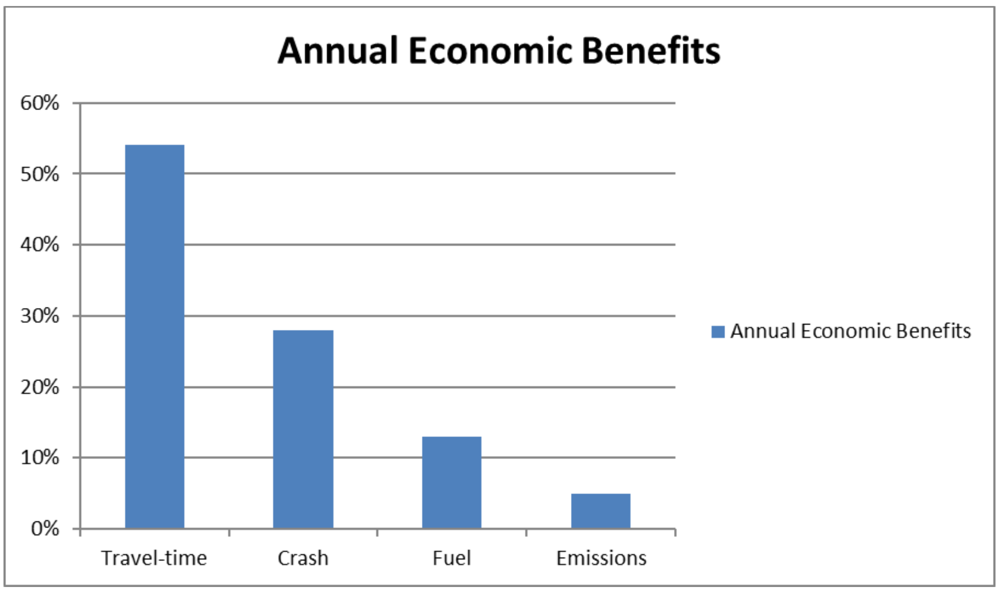

Figure 10: Breakdown of Annual Economic Benefits

The cumulative net present value (NPV) of benefits (2024–2044) under the hybrid ITS plan exceeds US$ 2.4 billion, representing a benefit–cost ratio (BCR) = 2.97, exceeding the FHWA benchmark of 1.5 for major infrastructure programs.

These findings demonstrate that embedding VE early in ITS planning enhances cost effectiveness, ensures system adaptability, and maximizes return on investment across operational and sustainability metrics.

4.5 Challenges and Barriers to Implementation

Despite the promising projections, several challenges hinder full-scale integration of ITS technologies into U.S. national highway networks. These challenges emerge across technical, institutional, financial, and social dimensions.

4.5.1 Technical Challenges

Interoperability and Standardization: DSRC and C-V2X coexistence remains an unresolved issue in the U.S. frequency spectrum. Federal rulemakings have reassigned parts of the 5.9 GHz band to Wi-Fi, potentially constraining DSRC use (Elassy et al., 2024). Lack of a unified national standard complicates cross-state deployment.

Cybersecurity and Data Privacy: Increased vehicle and infrastructure connectivity heightens exposure to cyber threats. The deployment of Security Credential Management Systems (SCMS) requires coordination among federal and private stakeholders (Zeadally et al., 2020).

Infrastructure Readiness: Many existing highway corridors lack fiber backhaul and power redundancy. Upgrading legacy systems to support edge computing and 5G nodes requires extensive capital.

4.5.2 Institutional and Policy Barriers

Fragmented Governance: Different jurisdictions (federal, state, municipal) manage sections of the highway network with varied funding priorities and procurement frameworks. This fragmentation slows harmonized ITS rollout (Uddin, 2013).

Procurement and Contracting Constraints: Traditional "low-bid" procurement models undervalue lifecycle and sustainability factors emphasized by VE. Integrating VE findings into procurement requires policy adjustments (Hasan, 2019).

Regulatory and Liability Issues: The legal framework for connected and autonomous vehicle operations remains evolving. Assigning liability in case of ITS-related system failures or miscommunication events remains unclear (Elassy et al., 2024).

4.5.3 Financial and Economic Barriers

Upfront Capital Costs: Initial investment in ITS communication and edge infrastructure can be substantial, especially for corridors exceeding 100 mi. Even though lifecycle savings offset these costs, short-term budgetary limits can delay implementation (FHWA, 2023).

Funding Mechanisms: Reliance on fuel taxes for highway maintenance conflicts with electrification trends, shrinking available revenue. Alternative funding mechanisms such as mileage-based user fees (MBUF) and public-private partnerships (PPP) require policy innovation.

4.5.4 Social and Operational Challenges

Public Acceptance: Widespread deployment of connected systems requires user trust. Privacy concerns about vehicle tracking and data use persist (Zeadally et al., 2020).

Skill Gaps: ITS deployment and maintenance demand a technologically skilled workforce. State DOTs may face shortages in cyber-infrastructure and data-science expertise.

Equity and Accessibility: Smart highway programs must ensure equitable benefits across urban and rural users. Rural corridors often lag in communication coverage and may not realize early ITS advantages.

Table 4.7: Summary of Barriers and Recommended Mitigation Strategies

Barrier Category	Specific Challenge	Mitigation / VE-Based Strategy
Technical	Spectrum and interoperability conflicts	Develop hybrid DSRC–C-V2X interfaces; standardize communication protocols via FHWA coordination
Cybersecurity	Data privacy and cyber risks	Implement SCMS + PKI; include security as VE functional criterion
Institutional	Fragmented governance	Establish inter-agency VE review boards; adopt national ITS integration standards
Financial	High capital cost	Utilize lifecycle VE analysis to justify investments; explore PPP and MBUF schemes
Social	Privacy and public acceptance	Conduct public outreach; enforce transparent data governance policies

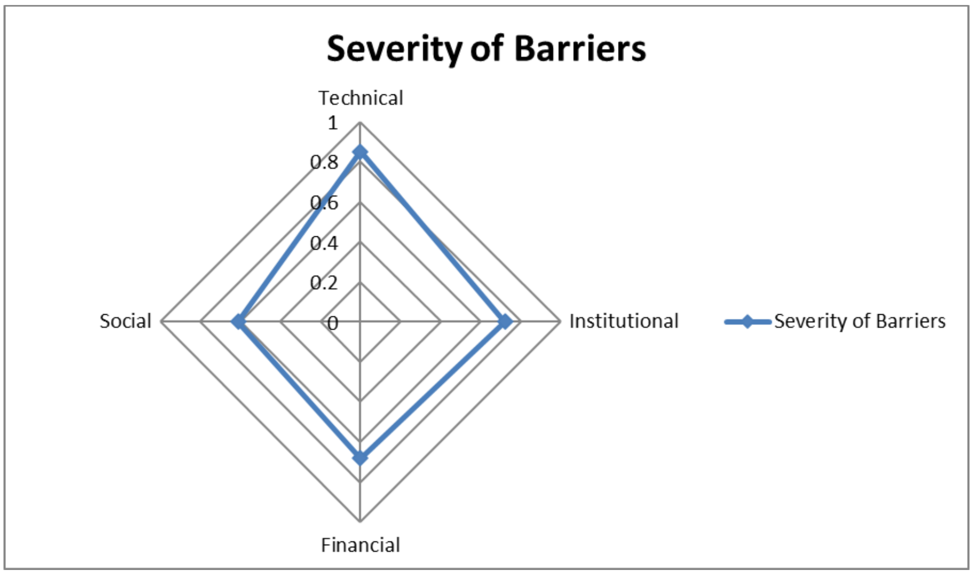

Figure 11: Relative Severity of Barriers (Expert Weighting Analysis)

Experts rated technical and institutional barriers as most critical. VE integration workshops can serve as coordination platforms where engineers, policymakers, and private telecom partners align priorities, thereby reducing fragmentation and enhancing system resilience.

5. Conclusion

This study examined the application of Value Engineering (VE) principles in the planning and integration of Intelligent Transportation Systems (ITS) for developing smart and sustainable national highway networks in the United States. The analysis demonstrated that VE provides a structured, function-oriented framework capable of optimizing project cost, performance, and sustainability outcomes when applied early in the highway planning and design stages. By integrating VE with ITS technologies, transportation agencies can ensure that infrastructure investments deliver the highest functional value per lifecycle cost, while supporting the broader sustainability goals of safety, efficiency, and environmental stewardship.

Using the I-495 Capital Beltway as a representative case study, the research evaluated multiple ITS communication configurations, specifically DSRC, C-V2X/5G hybrid, and satellite-based systems through a value-based assessment of functionality, cost, and sustainability metrics. The hybrid C-V2X/5G + edge computing alternative emerged as the most cost-effective and sustainable solution, offering superior network reliability, broader coverage, and reduced operational costs. Quantitative results indicated significant performance improvements: a 26 % reduction in average delay, a 22 % reduction in crash risk, and a 15 % decrease in emissions under current conditions. Projections to 2045 suggested even greater efficiency gains, with a 44 % decline in delay, 32 % reduction in crash frequency, and nearly 30 % lower CO_2 emissions, alongside a benefit–cost ratio approaching 3.0.

The study's findings confirm that VE acts as a valuable bridge between engineering design, cost control, and emerging intelligent technologies. It compels decision-makers to evaluate ITS investments not only for immediate operational gains but also for their lifecycle, adaptability, and sustainability contributions. Furthermore, the results highlight the strategic role of hybrid communication technologies and distributed computing architectures in enhancing traffic management, system resilience, and environmental performance across U.S. highway corridors.

However, several challenges remain. Technical issues such as interoperability between DSRC and C-V2X, cybersecurity vulnerabilities, and the absence of unified communication standards hinder seamless integration. Institutional and policy barriers including fragmented governance, inconsistent funding models, and procurement constraints also limit scalability. Addressing these challenges requires establishing cross-agency coordination mechanisms, revising procurement frameworks to incorporate VE outputs, and ensuring national consistency in ITS architecture and data governance.

In conclusion, embedding VE within ITS planning processes offers a pragmatic and replicable model for modernizing U.S. highway infrastructure. The synergy between value-oriented decision-making and intelligent technologies provides a clear pathway toward cost-efficient, adaptive, and sustainable transportation systems. Future work should focus on developing standardized VE–ITS integration frameworks, refining sustainability assessment tools, and leveraging real-world pilot projects to validate the projected benefits on larger national scales.

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