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A Mathematical Model for Assessing the Economic and Social Impacts of Traffic Congestion an Applied Study on Riyadh City

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ABSTRACT

This paper develops and applies a comprehensive mathematical model to quantify the economic and social impacts of traffic congestion in Riyadh, the capital city of Saudi Arabia, which faces significant mobility challenges. A multi-dimensional assessment framework is proposed, integrating three core mathematical models: the Congestion Level Model (synthesizing 17 variables for a unified index), the Economic Impact Model (translating the index into costs for fuel, maintenance, and productivity loss), and the Social Impact Model (assessing consequences for time wasted, public health, and safety). The analysis utilizes a 10-year longitudinal dataset (2015-2024) specific to Riyadh, with model coefficients calibrated to the local context. The model application reveals a persistent upward trend in congestion severity over the past decade. The analysis estimates the annual economic burden to be substantial, with productivity losses representing the dominant cost component. Social impacts are equally severe, with wasted commuter time and negative health outcomes being the most significant societal burdens. The model shows strong correlations between population growth, urban density, and rising congestion levels. This study presents one of the first comprehensive, model-based frameworks for quantifying the dual economic and social dimensions of traffic congestion in a major Saudi Arabian city. The findings provide critical, evidence-based insights for policymakers, offering a robust analytical tool for evaluating mitigation strategies and informing investment priorities aligned with Saudi Arabia's Vision 2030 objectives.

Keywords: Traffic Congestion, Economic Impact, Social Impact, Mathematical Modeling, Urban Mobility, Riyadh, Saudi Arabia, Transportation Policy, Vision 2030

INTRODUCTION

Background and Global Context

Urbanization is undoubtedly one of the most salient processes of the last century. As the populations continue to concentrate in the areas of the metropolis, the city has naturally become the key generator of economic activity, innovation, and cultural progress. Simultaneously, accelerated urban expansion has resulted in the proliferation of various challenges, with traffic congestion proving one of the most acute and universal ones. From East Asia megacities' immense campuses and Europe and America's well-established urban hubs, congested streets are at the forefront of hundreds of millions of individuals' daily routine. Yet it goes beyond the mere issue of convenience; traffic congestion is a severe drain on economic productivity, amenace to environmental sustainability, and a massive detriment to urban quality of life.

Congestion imposes economic costs on several dimensions. The most substantial direct costs are the wasted fuel, the increased wear and tear on vehicles, and the delays to freight and logistics. In just one year, the United

States spent nearly $87 billion on congestion-induced lost productivity. American trucking industry congestion expenses totaled over $108 billion in 2022 (World Economic Forum, 2019; ATRI, 2024). These statistics show how inefficient transportation systems impose a significant economic burden. In addition to direct costs, congestion has substantial negative externalities. Commuters are affected by high levels of stress. They lose the time that could be spent with their families or engaged in leisure activities. Finally, increased air and noise pollution contribute to a range of public health problems (Zhang & Batterman, 2013; Levy et al., 2010).

The social dimensions of congestion are equally profound. Research has consistently demonstrated that long commute times are associated with lower life satisfaction and reduced civic engagement (Noland & Lemieux, 2006; Putnam, 2000). The time lost to traffic represents a direct reduction in the time available for personal development, family life, and community participation. Furthermore, the health impacts of traffic-related air pollution—including respiratory illnesses, cardiovascular disease, and premature mortality—impose a significant burden on public health systems and individual well-being (Zhang & Batterman, 2013).

The Middle East and GCC Context

The Middle East in general and the nations of the Gulf Cooperation Council, in particular, is a distinct and intriguing addition to the story of worldwide urban congestion. The GCC nations, such as Qatar, Saudi Arabia, and the United Arab Emirates, have experienced a level of economic and urban growth unmatched in the last few decades. All of them witnessed a significant increase in population levels, large-scale infrastructure programs, and extremely high rates of motorization. Some of their towns, such as Abu Dhabi, Dubai, Doha, or Riyadh, have quickly developed into global centers, but the transportation system has been unable to satisfy the rapidly increasing levels of demand. Consequently, the economic strength and living criteria that drew people and businesses to these cities are now at risk due to constant traffic congestion.

The severity of congestion in GCC cities is the result of several structural factors. First, the region's urban form intensifies the traffic load. After all, the lower density is sprawl, and it originated at a time when the territories were significantly more significant, and the fuel had a low price. This structure will inevitably generate a high volume of vehicle travel and distort an economically feasible form of public transportation (Abubakar & Alshammari, 2023). Secondly, the region's average level of disposable income and historically low fuel prices have supported a cultural level of dependence on cars: the private vehicle ownership ratio is one of the highest in the world. Thirdly, the harsh climatic conditions in most of the GCC states make walking and cycling unattractive for most of the year, which ultimately increases the need for motorized forms of transport. The last point, with the difficulty of direct influence, is the poorly developed public transport system.

Recent research has begun to document the scale of the challenge. A study by Roland Berger (2022) explicitly identified Dubai and Riyadh as cities grappling with severe congestion that hampers their economic potential and quality of life. UN-Habitat (2013) highlighted the systemic challenges of car-dependent urban planning across the Middle East and North Africa region, noting that the transportation sector accounts for a disproportionate share of energy consumption and greenhouse gas emissions. Al-Haji et al. (2024) compared transportation systems in EU and GCC countries, finding that GCC cities lag significantly in the provision of sustainable mobility options and the integration of intelligent transportation systems.

The Case of Riyadh City

The case of Riyadh, the capital of the Kingdom of Saudi Arabia, is a showcase of the GCC challenges associated with hyper-growth. In the 1960s, the city's population was just over 150,000 people; today, it is estimated at over 8 million people and continues to grow rapidly . The demographic explosion was accompanied by an even more significant spread in a horizontal projection; today's Riyadh is a 1,800-square-kilometer low-density urban sprawl. The main mode of transportation for the residents of the city is a private car, and not so many alternatives are available. In addition, a high level of household incomes, as well as historically low fuel costs, only contribute to more efficient auto-dependent behavior.

Consequently, Riyadh now grapples with some of the most severe traffic congestion in the region, a problem that is readily apparent on its major freeways and arterial roads, particularly during peak hours. The congestion is not merely a transportation issue; it has profound implications for the city's economic competitiveness, environmental sustainability, and the quality of life of its residents. Early research by Al-Mosaind (1998) documented the emergence of freeway congestion in Riyadh and explored driver attitudes toward potential policy interventions. More recent studies have confirmed that the problem has intensified. Al-Majhad and Bramantoro (2018) proposed an IoT-based framework for a "smart city" approach to managing traffic, acknowledging the high economic costs of congestion.

Initial estimates provide the first evidence of the severity of the problem. Although there has been no holistic model-based evaluation of all negative side effects, even those based on current research indicate that the economic damage of excessive congestion levels of traffic in Riyadh may amount to billions of Saudi Riyals annually.

However, this number significantly underrepresents the actual cost of such congestion since it does not fully evaluate major health and environmental externalities. Commuting issues influence the quality of people's lives, decrease business performance, and limit the city's attractiveness for residents and workers.

Research Problem and Significance

There is a significant void in the integrated evaluation of the effects of traffic congestion in the Saudi cities. While previous research was primarily qualitative, only particular concerns, road safety, or travel delays were considered. A comprehensive, evidence-based approach to estimating the cost of congestion is needed. In its absence, public officials are forced to proceed with infrastructure decisions based on incomplete information. In the present case, my research develops a model for Riyadh, presents a method for presenting its flexibility to other cities, and recovers the estimates and uses of empirical results as a choice in the evaluation tool for potential policy actions. The evidence presented on social indicators makes my research consistent with the aims of Saudi Vision's 2030.

Research Objectives

To address the identified research problem, this paper pursues the following primary objectives:

1 **To develop a comprehensive mathematical model** that quantifies the relationship between key urban and transportation variables and the level of traffic congestion.
2 **To quantify the direct and indirect economic impacts** of traffic congestion in Riyadh, including costs related to fuel, vehicle maintenance, and lost productivity.
3 **To assess the multifaceted social impacts** of traffic congestion, including time waste, public health consequences, and effects on social connectivity and safety.
4 **To apply the model to a longitudinal dataset** for Riyadh to analyze trends in congestion and its associated costs over the past decade (2015-2024).
5 **To provide data-driven policy recommendations** for mitigating traffic congestion and enhancing urban mobility and quality of life in Riyadh, aligned with Saudi Vision 2030 objectives.

Organization of the Paper

The structure of the paper is as follows. Section 2 offers a review of the literature on the economic and social impacts of traffic congestion in general and modeling methods in particular with emphasis on the Middle East. Section 3 describe the theoretical framework and methodology of all three mathematical models. Section 4 provides detailed information about data sources and descriptive statistics of the variables selected for analysis. Section 5 reports the main findings of the research in the form of the estimated levels of congestion and the costs associated with it. Section 6 discusses the findings, limitations and compares them to the results of previous studies. Section 7 summarize the key findings and completes the paper with policy recommendations.

LITERATURE REVIEW

This section provides a comprehensive review of the scholarly literature that forms the foundation for this study. It is organized into four main parts: a discussion of the economic impacts of traffic congestion, an examination of its social impacts, an overview of mathematical modeling approaches used to quantify these effects, and a focused review of research on transportation challenges in Saudi Arabia and the GCC region.

Economic Impacts of Traffic Congestion

The economic impact of traffic congestion on most developed urban centers has been a subject of extensive research for several decades. The costs are often broken down into direct and indirect costs on individuals, firms, and the overall economy. The common direct costs include the increased costs of vehicle operation and the opportunity cost of the value of time lost. Firstly, Congestion disrupts the very conditions under which vehicle operation is efficient. Slow-moving and stop-and-go traffic forces autos and trucks to use more gasoline than when they are operating efficiently. Economists Small and Winston (1999) showed that congestion leads to higher spending on gasoline by ordinary people as early as the 1990s. Second, the rate of repair or maintenance of automobiles deteriorates faster than it should. Brakes, engines, and transmissions should last much longer than they generally do, and each subsequent part replacement is highly expensive. It makes the value of automobile ownership increase from one year to the next.

Losses in Production and Cost of Time: Time Cost of congestion is probably most extensively researched of all its consequences from an economic perspective. Those stuck in traffic cannot use the time as pointed out by Button and Verhoef (2001) driver, passenger or passenger to generate income or otherwise make effective use of life itself. As a column distorted straight (2001) c for productive time is just a straight loss of economic output. Traffic congestion times different loss magnitudes Press set up by the value of trip time Button and Verhoef (2001). This is a particularly serious problem for freight vehicles, which suffer from increased operational costs and decreased efficiency. Figliozzi (2010) argues that congestion causes disorder in production arrangements, increases freight transport costs and undermines supply reliability for merchants, resulting in higher consumer prices. This was compounded by Weisbrod et al. (2003) who showed congestion may not only block effective market areas of business. It also prevents the local agglomeration economies cooperation of urban life and production that is so crucial to urban productivity.

Broader Economic Effects and Empirical Evidence: The cumulative effect of these costs extends to the macroeconomic level. The Texas Transportation Institute, in its long-running Urban Mobility Report (2021), has consistently documented multi-billion dollar annual losses for national economies due to congestion. These costs can deter investment, reduce a city's competitiveness, and act as a barrier to economic growth. Fattah et al. (2018) provided a recent synthesis, confirming that congestion increases travel time, fuel use, and greenhouse gas emissions while reducing the productive working hours of the labor force. The American Transportation Research Institute (2024) quantified the cost to the trucking industry alone at over $108 billion in 2022, underscoring the profound impact on logistics and commerce.

Urban sprawl causes transportation costs. This connection has been described in great detail. According to Litman (2021), the English language for urban sprawl as developed today America's Grass Burrs. A study by The New Climate Economy (2015) found that people living in such development patterns pay more than those who do not. On a per capita basis, the costs for transportation are three times per capita of incomes. The New Climate Economy published in 2015 calculated a price-tag of over one trillion dollars per year on the US economy - if one includes such expenses as infrastructure (such as over here you need parking lots), transportation and public service support.

Social Impacts of Traffic Congestion

While economic costs are more easily monetized, the social impacts of traffic congestion on individual and community well-being are arguably just as significant. These impacts affect public health, social cohesion, and overall quality of life.

Public health ramifications: The correlation between traffic congestion and poor health are no secret at all. The most direct route is pollution in the air. In situations of slow-moving or stopped traffic, a great many exclusive pollutants exist in the immediate locality- particulate matter (PM2.5), nitrogen oxides (NOx), volatile organic compounds (VOCs) and more. Zhang and Batterman (2013) discovered that traffic-related air pollution is linked to all sorts of health problems, including respiratory diseases cardiovascular disease, and raised mortality levels back then. They also estimated that traffic air pollution is responsible for thousands of premature deaths each year in big cities. Levy et al. (2010) verified in detail the public health consequences of PM2.5 caused by congestion, showing that they led to heavier health burdens and associated hospital costs. In addition to the air pollution problems there, this traffic noise presents another major stress factor. It leads to sleep disorders, hypertension and heart disease. Being stuck in traffic gives rise to a intense sense of frustration and constant stress–finds now revealed as being related to mental as well as physical disabilites in some earlier studies on this topic (Stokols & Novaco, 1978).

Quality of life and time use: The time spent in traffic congestion directly reduces both the time we have available for personal or social activities on one hand as well as our overall quality of lives apart from this inconvenience. This interesting phenomenon is called "time poverty", and it significantly lowers the standard of living for all concerned: instead of hours meant to be with family members or for fun as well community service events, these only serve as time spent traveling. However, losses in one's private time thus acquired have other serious consequences. Social isolation and decreased civic involvement are likely outcomes.

Social capital and community severance: Robert Putnam (2000) observed, in his influential book about social capital, that ever-longer commutes may indeed be a key reason why people join fewer clubs or groups for hobbies and associate with other citizens less often in contemporary societies. The time consumed by commuting detracts from opportunities to take part in community organizations and clubs, volunteer activities, or informal conversations with friends who may soon become casual acquaintances. Anciaes et al. (2016) discussed traffic impacts and public opinion. They found that community isolation—as when heavy road traffic divides neighborhoods both physically and socially —is an important issue to residents. A rich traffic flow can make it difficult or even impossible but simply awkward for people in the neighborhood to cross roads, fetch daily necessities, or maintain contact with those close neighbors. Particularly affected may be groups such as children, the aged and individuals with reduced mobility.

Mathematical Modeling Approaches

To quantify the diverse impacts of congestion, researchers have employed a variety of mathematical and econometric modeling techniques. These models range in complexity from simple trend analysis to sophisticated system dynamics and multi-criteria decision models.

Econometric and Statistical Models

This paper continues in the tradition of the economics modeling that seeks to establish statistical correlations among various explanatory variables and some defined outcome, such as congestion levels or costs related to congestion. Common methodologies include multiple regression analysis (OLS, etc), time series analysis and panel data techniques.Originally published in English on March 31 2017; Translated by Habib Kiebler. Authors In the case of GT the traffic congestion model proposed by Wenbin Hu et al. (2018) served as a crucial benchmark, indicating how various factors can be integrated into a unified assessment model for both the social and economic repercussions.

Traffic Flow and Simulation Models: In recent years, the focus of research has been on refining traffic flow models and developing urban traffic simulation systems. Ulvi et al. (2024) ’ taking this trend further introduced UTMOM (Urban Traffic Mobility Optimization Model) a data-driven technique geared South for analyzing urban traffic datasets as well as predicting congestion patterns.Hu et al.'s (2018) Actual Urban Traffic Model (AUTM) is an actual city traffic simulation model fitting for predicting and alleviating traffic jams, Hence Institutions can study the effectiveness of its computer-assisted simulation in policy evolution. Khorani et al. (2011) proposed a mathematical model for urban traffic optimization utilizing an imperialist competitive algorithm (ICA), demonstrating the viability of optimization methods in traffic management.

Integration of Technology and Smart Systems: The emergence of smart city technologies has opened new avenues for traffic modeling and management. Guerrero-Ibáñez et al. (2015) discussed the integration challenges of intelligent transportation systems with connected vehicle, cloud computing, and Internet of Things technologies. These technological advances enable real-time data collection and dynamic traffic management, which can be incorporated into predictive models.

Transportation Challenges in Saudi Arabia and the GCC

Within the Middle East and GCC region, research on traffic congestion has been growing, though it remains less developed than in other regions. Studies have often focused on specific cities and particular aspects of the problem.

Saudi Arabia Specific Research: In a initial report on congestion in Riyadh， representing its North American drivers as well, (Mosaind， 1998) concentrate any road do more study on freeway congestion in Riyadh. The results showed that although drivers recognized the seriousness of congestion, there was little drive for people to try something different in transportation mode or take part in demand-reducing administrative policies. Aldalbahi, Walker (2015) conducted empirical research on the relationship between urban growth patterns and traffic problems in Riyadh. Planning and investment have both lagged far behind demand for infrastructure. They recommended the establishment of urban growth limits as a policy to control sprawl and reduce vehicle travel demand.

GCC Regional Context: Research in the wider Gulf region appears to confirm that the problems facing Riyadh are also shared by its neighbours. Abubakar and Alshammari (2023) studied urban planning schemes in the GCC to create low-carbon cities. Their research showed that cities in GCC Member States have population densities far below the 15,000 persons/km² which UN-Habitat Guidance requires for sustainable urban environments. For this kind of environment, such low densities are difficult to organize in a way that makes economically viable the supply of characters percent in name-only public transit systems to match lands being developed on rare golden city streets. Asmyatullin and Tyrkba (2020) made a comparative study of smart cities in the Gulf Cooperation Council, looking at the financial dimension. They found that, while GCC countries were making heavy investment both in smart city measures and developments of infrastructure, such as intelligent transportation systems, throughout this whole period setup and rule was not followed uniformly. writelisicing

Al-Haji, et al. (2024) compared sustainable urban transport systems in EU and GCC countries, They found that EU cities accord premier ranking to walking, bicycling, taking public transportation and cars in order to meet a city's transportation needs. GCC cities, by contrast, put cars first. The study highlighted the need for GCC cities to invest more in non-motorised transport and public transport for sustainable mobility.

Policy and Planning Context: UN-Habitat (2013) reviewed sustainable urban mobility in the Middle East and North Africa, identifying mixed land use and good public transport as key issues, formulating 17 recommendations to overcome these challenges. Roland Berger (2022) identified Transit-Oriented Development (TOD) as one of two principal strategies for GCC urban development. In their approach to TOD, which is both in line with their policy and has produced positive results, 20 stations are being built around metro or monorail lines as fast as possible and then commercial districts developed nearby.

Research Gap: However, there is a significant lack in the comprehensive module. One problem is that "Most of the studies are qualitative, only focused on one aspect. The problem is not that the total cost of such a mass transit could not be estimated." The vast majority of the costs came directly from the people themselves. This paper intends to rid us of this difficulty by providing a useful analysis tool for Riyadh and transport planning elsewhere.

THEORETICAL FRAMEWORK AND METHODOLOGY

This section outlines the analytical foundation of the study. It begins by presenting the conceptual framework that illustrates the causal relationships between the drivers of congestion and its impacts. It then details the development of the three core mathematical models used for the assessment. Finally, it describes the operationalization of variables and the statistical methods employed for analysis.

Conceptual Framework

The theoretical approach of this study is grounded in a systems perspective of urban mobility. Traffic congestion is not viewed as an isolated problem but as an emergent property of a complex system of interacting components. Drawing on the work of integrating insights from urban economics (Glaeser & Kahn, 2004) and transportation demand theory (Litman, 2021), the conceptual framework organizes these components into three distinct but causally linked stages: **Drivers**, **Congestion**, and **Impacts**.

- **Drivers of Congestion**: The environmental and transportation capacity affect road service demanded, those that increase traffic congestion (population growth, urban dispersion, construction projects, growth in car ownership) or alleviate it (road capacity public transportation, traffic management by car pooling from office hours). Here congestion is also put forward as one of maladjustment between supply and demand in the transport system.
- **Congestion Level**: This portion of the model is the transportation system's state when demand surpasses supply. It's an unspecified variable which can be quantified using various proxies. The model sums these outputs into a contrastive index of seriousness, and this approach accords fairly well with the composite indicator methodologies in urban studies.
- **Impacts of Congestion**: At this point, it was the impact of the traffic jams on the urban environment and people in particular. But Social impacts involve lower living standards as well as wasted time, the erosion of public health, declining social networks and secure conditions far into night or early morning hours.

This framework posits a clear causal pathway: the interplay of various urban and transportation drivers determines the level of traffic congestion, which in turn produces a range of negative economic and social impacts. The methodology is designed to quantify the relationships at each stage of this causal chain, providing a comprehensive assessment tool.

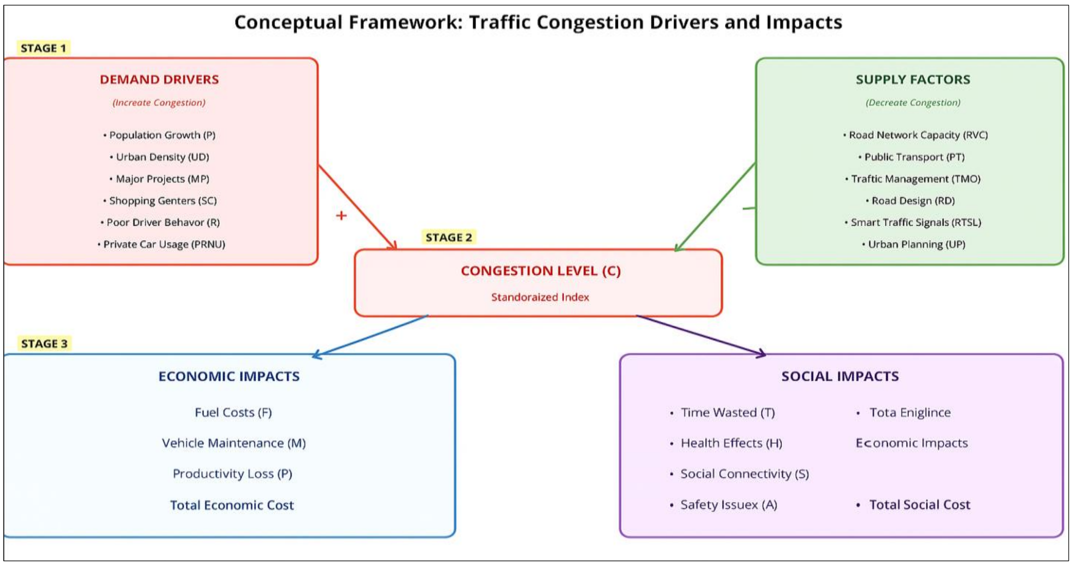

Figure 1. Conceptual Framework of Traffic Congestion Drivers and Impacts

Mathematical Model Development

To operationalize the conceptual framework, a suite of three mathematical equations was developed. These models are designed to be both theoretically grounded and empirically applicable, using variables that are measurable and relevant to the Riyadh context. The model structure follows the approach of Hsu and Wang (2018) but is adapted and extended to incorporate additional factors relevant to the GCC context.

Equation 1: The Congestion Level Model (C)

The first model calculates a standardized Congestion Level (C) as a weighted sum of various contributing and mitigating factors. The model is specified as a linear equation, where each variable is multiplied by a coefficient (α or β) representing its relative impact on congestion. The coefficients are derived from the existing literature and adapted for this study based on expert judgment and the specific characteristics of Riyadh.

The equation for the Congestion Level (**C**) is:

$$\mathbf{C} = (\alpha_P \cdot P + \alpha_{UD} \cdot UD + \alpha_{MP} \cdot MP + \alpha_{SC} \cdot SC + \alpha_{DB} \cdot DB + \alpha_{PRNU} \cdot PRNU) - (\beta_{RNC} \cdot RNC + \beta_{PTI} \cdot PTI + \beta_{CPW} \cdot CPW + \beta_{TMO} \cdot TMO + \beta_{RDI} \cdot RDI + \beta_{RND} \cdot RND + \beta_{UP} \cdot UP + \beta_{BR} \cdot BR + \beta_{RTSL} \cdot RTSL + \beta_{ROP} \cdot ROP) + \beta_{NRAC} \cdot NRAC$$

Aggravating Factors (Increase Congestion C)

These factors contribute **positively** to the overall congestion level, weighted by their α or β_{NRAC} coefficients:

- **P** (Population): Weighted by $\boldsymbol{\alpha_P}$.
- **UD** (Urban Development): Weighted by $\boldsymbol{\alpha_{UD}}$.
- **MP** (Major Projects): Weighted by $\boldsymbol{\alpha_{MP}}$.
- **SC** (Shopping Centers): Weighted by $\boldsymbol{\alpha_{SC}}$.
- **DB** (Driver Behavior): Weighted by $\boldsymbol{\alpha_{DB}}$.
- **PRNU** (Private Car Usage): Weighted by $\boldsymbol{\alpha_{PRNU}}$.
- **NRAC** (Natural Resource Accessibility Changes): Weighted by $\boldsymbol{\beta_{NRAC}}$.

Mitigating Factors (Decrease Congestion C)

These factors reduce the overall congestion level, as their weighted sum is **subtracted** from the aggravating factors. They are all weighted by β coefficients:

- **RNC** (Road Network Capacity): Weighted by $\boldsymbol{\beta_{RNC}}$.
- **PTI** (Public Transportation Infrastructure): Weighted by $\boldsymbol{\beta_{PTI}}$.
- **CPW** (Carpooling and Work-from-home policies): Weighted by $\boldsymbol{\beta_{CPW}}$.
- **TMO** (Traffic Management Operations): Weighted by $\boldsymbol{\beta_{TMO}}$.
- **RDI** (Road Design Improvements): Weighted by $\boldsymbol{\beta_{RDI}}$.
- **RND** (Road Network Development): Weighted by $\boldsymbol{\beta_{RND}}$.
- **UP** (Urban Planning): Weighted by $\boldsymbol{\beta_{UP}}$.
- **BR** (Bypass Roads): Weighted by $\boldsymbol{\beta_{BR}}$.
- **RTSL** (Real-time Signal Lights): Weighted by $\boldsymbol{\beta_{RTSL}}$.
- **ROP** (Road Optimization): Weighted by $\boldsymbol{\beta_{ROP}}$.

The theoretical justification for this additive linear structure is that congestion is fundamentally a function of the balance between demand-generating factors and supply-enhancing factors. While non-linear relationships may exist (e.g., network effects, threshold effects), the linear approximation provides a tractable and interpretable first-order model that captures the primary relationships.

Equation 2: The Economic Impact Model (E_Econ)

The second model quantifies the total economic impact of congestion. It posits that the economic cost is a function of the congestion level (C) itself, as well as its direct consequences on fuel costs (F), vehicle maintenance costs (M), and productivity losses (P). Each component is weighted by a coefficient (γ) to reflect its contribution to the total economic burden. This specification recognizes that congestion imposes costs through multiple channels, each of which can be separately identified and quantified.

The Total Economic Impact Equation (Revised)

The equation models the **Total Economic Impact** ($\mathbf{E_{Econ}}$) as a linear function of congestion (C) and the associated costs (Wasted Fuel, Maintenance, and Productivity Loss):

$$\mathbf{E_{Econ}} = \gamma_C \cdot C + \gamma_F \cdot F + \gamma_M \cdot M + \gamma_P \cdot P$$

Variable and Coefficient Meanings

- $\mathbf{E_{Econ}}$: Represents the **Total Economic Impact**. This is the dependent variable, typically quantified in monetary terms (e.g., Saudi Riyals), reflecting the overall economic cost attributable to congestion.

Cost Components and Their Coefficients (γ_i):

- **C**: The **Congestion Level** derived from Equation 1. It is weighted by $\boldsymbol{\gamma_C}$, the impact coefficient for direct congestion costs.
- **F**: The **Wasted Fuel Cost**. This cost is weighted by $\boldsymbol{\gamma_F}$, the impact coefficient for fuel consumption inefficiencies.
- **M**: The **Increased Maintenance Cost**. This cost is weighted by $\boldsymbol{\gamma_M}$, the impact coefficient for accelerated vehicle wear and tear.
- **P**: The **Productivity Loss Cost** (previously P_{loss}). This cost is weighted by $\boldsymbol{\gamma_P}$, the impact coefficient for lost working hours and shipment delays.
- $\boldsymbol{\gamma_i}$: The **Impact Coefficients** ($\gamma_C, \gamma_F, \gamma_M, \gamma_P$) reflect the relative **economic weight or severity** of each corresponding cost component on the total economic impact.

In essence, the model calculates $\mathbf{E_{Econ}}$ by summing the economic costs from direct congestion and the indirect costs it generates (fuel, maintenance, and lost time), scaled by their relevant economic multipliers.

The economic impact model draws on the extensive literature on the costs of congestion (Weisbrod et al., 2003; Figliozzi, 2010; ATRI, 2024). The weights (γ) are calibrated based on empirical studies of the relative magnitude of different cost components. Productivity losses typically represent the largest component, reflecting the high value of time for both passenger and freight transport.

Equation 3: The Social Impact Model (E_Soc)

The third model assesses the social costs of congestion. It is structured similarly to the economic model, calculating the total social impact as a weighted sum of four key components: time wasted (T), negative health effects (H), reduced social connectivity (S), and adverse impacts on road safety (A). Each component is weighted by a coefficient (δ) to reflect its relative importance in the overall social burden.

The equation calculates the **Total Social Impact** ($\mathbf{E_{Soc}}$) as a linear sum of weighted social costs associated with congestion:

$$\mathbf{E_{Soc}} = \delta_T \cdot T + \delta_H \cdot H + \delta_S \cdot S + \delta_A \cdot A$$

Variable and Coefficient Meanings

- $\mathbf{E_{Soc}}$: Represents the **Total Social Impact**. This is the final output, measuring the non-economic cost to society. It can be expressed either as a composite index value or monetized (assigned a financial value).
- $\boldsymbol{\delta_i}$: The **Impact Coefficients** ($\delta_T, \delta_H, \delta_S, \delta_A$). These are weights that reflect the relative **social importance or severity** of each corresponding cost component on the total social impact.

Components of Social Cost:

- **T**: The cost associated with **Time Wasted**. This quantifies the value of non-productive time lost by individuals due to traffic delays. It is weighted by $\boldsymbol{\delta_T}$.
- **H**: The cost associated with adverse **Health effects**. This includes consequences like respiratory problems from air pollution and psychological stress from prolonged, difficult commutes. It is weighted by $\boldsymbol{\delta_H}$.
- **S**: The cost associated with reduced **social interaction**. This represents the lost opportunities for family, friends, or leisure activities due to extended time spent commuting. It is weighted by $\boldsymbol{\delta_S}$.
- **A**: The cost associated with compromised road **Safety**. This reflects the social costs (injuries, fatalities, emotional distress) from increased accidents and risk due to congestion. It is weighted by $\boldsymbol{\delta_A}$.

In essence, $\mathbf{E_{Soc}}$ captures the **human and community burden** of traffic congestion by aggregating the weighted costs to well-being, health, and quality of life.

The social impact model is grounded in the literature on quality of life, public health, and social capital (Putnam, 2000; Noland & Lemieux, 2006; Zhang & Batterman, 2013; Levy et al., 2010; Anciaes et al., 2017). The weights (δ) reflect the relative severity and prevalence of each type of impact. Time wasted and health effects typically dominate, but the model also captures the important but often overlooked impacts on social connectivity and safety.

Variable Operationalization

Each variable included in the models was carefully defined and operationalized based on available data for Riyadh. The variables, their definitions, measurement units, and data sources are summarized in Table 1.

Table 1. Variable Definitions, Measurement Units, and Data Sources

Category	Variable	Code	Description	Unit	Data Source
Demand Drivers	Population	P	Total population of Riyadh	Millions	Saudi General Authority for Statistics
	Urban Density	UD	Population per square kilometer	Persons/km²	Riyadh Development Authority
	Major Projects	MP	Number of active large-scale construction projects	Count	Ministry of Municipal Affairs
	Shopping Centers	SC	Number of major commercial malls	Count	Local business directories
	Driver Behavior	DB	Index of driving quality and compliance	1-10 scale	Expert assessment
	Private Car Usage	PRNU	Percentage of trips by private car	Percentage	Transport surveys
Supply Factors	Road Network Capacity	RNC	Total length of road network	Kilometers	Ministry of Transport
	Public Transport Infrastructure	PTI	Index of availability and quality	1-10 scale	Expert assessment
	Carpooling/Work from Home	CPW	Percentage of workforce	Percentage	Labor force surveys
	Traffic Management Operations	TMO	Index of effectiveness	1-10 scale	Expert assessment
	Road Design Improvements	RDI	Index of quality	1-10 scale	Expert assessment
	Road Network Development	RND	New road kilometers added annually	Kilometers	Ministry of Transport
	Urban Planning	UP	Index of effectiveness	1-10 scale	Expert assessment
	Bypass Roads	BR	Number of major bypasses	Count	Ministry of Transport
	Real-time Signal Lights	RTSL	Number of smart traffic signals	Count	Traffic management authority
	Road Optimization	ROP	Index of network efficiency	1-10 scale	Expert assessment
	Natural Resource Accessibility	NRAC	Index of change	Index	Expert assessment
Outcomes	Congestion Level	C	Standardized congestion index	Index	Calculated
	Economic Impact	E_Econ	Standardized economic cost index	Index	Calculated
	Social Impact	E_Soc	Standardized social cost index	Index	Calculated

Source: Data retrieved and analyzed from eyas70/Traffic-Congestion-Model (2025).

Data Collection and Standardization: We got data from a variety of formal sources including the Saudi General Authority of Statistics, the Riyadh Development Authority, Transport Ministry or on the status of streets, experts were brought to bear and measures came that way. In examples where direct measurement was impractical (e.g., driver behavior, traffic management effectiveness), expert assessments were made to develop indices on a 1-10 scale. This kind of methodology fits perfectly into international urban benchmarking study that need to take a comprehensive approach. (Asmyatullin & Tyrkba and Ji, 2020).

To ensure that variables measured on different scales could be compared and integrated into the model, all independent variables were standardized using the z-score method before being entered into the congestion equation. This transformation converts each variable to have a mean of 0 and a standard deviation of 1, allowing for a more direct interpretation of their relative coefficients and facilitating comparison across variables.

Statistical Analysis Methods

The analysis was conducted using a combination of descriptive and inferential statistical techniques, implemented in Python using the statsmodels, scikit-learn, pandas, matplotlib, and seaborn libraries.

- **Descriptive Statistics**: Standard measures of central tendency (mean, median) and dispersion (standard deviation, range) were calculated for all variables to summarize the data and identify trends over the 10-year period. Time series plots were created to visualize the evolution of key variables.
- **Correlation Analysis**: A Pearson correlation matrix was generated to examine the bivariate relationships between all variables. This was used to identify potential multicollinearity issues and to understand the associations between different drivers of congestion. Correlation coefficients were tested for statistical significance at the 0.05 level.
- **Multiple Regression Analysis**: The core of the inferential analysis was an Ordinary Least Squares (OLS) multiple regression model. The standardized independent variables were used to predict the calculated Congestion Level. This analysis served to validate the structure of the Congestion Level Model and to test the statistical significance of the individual driver variables. Model fit was assessed using the R-squared and Adjusted R-squared statistics, while the overall significance of the model was tested using the F-statistic. Individual coefficients were tested using t-statistics.
- **Time Series Analysis**: Trend analysis was conducted to identify patterns and changes in congestion levels and impacts over time. This included visual inspection of time series plots and calculation of year-over-year growth rates for key variables.

DATA AND DESCRIPTIVE STATISTICS

This section details the data used for the study, covering the sources, the time period, and the key characteristics of the dataset. It provides a statistical and visual overview of the primary variables that underpin the analysis.

Data Sources and Collection

The data for this research were compiled from a variety of official and public sources to create a comprehensive, longitudinal dataset for Riyadh city. The dataset covers a 10-year period from 2015 to 2024, with data collected on an annual basis. This time frame was chosen to capture the dynamics of urban growth and transportation system changes in Riyadh in the years leading up to and following the launch of Saudi Arabia's Vision 2030 in 2016. The primary data sources included:

- **Demographic Data (P, UD)**: Population and urban density figures were based on data from the Saudi General Authority for Statistics (GASTAT) and the Riyadh Development Authority. These are official government statistics published annually.
- **Infrastructure Data (MP, SC, RNC, RND, BR, RTSL)**: Information on major projects, road network length, and other infrastructure components was gathered from publications by the Ministry of Municipal and Rural Affairs, the Ministry of Transport, and public announcements. Data on major projects were compiled from news sources and official project announcements. Shopping center data were obtained from local business directories and real estate databases.
- **Transportation System Data (PTI, CPW, TMO, RDI, ROP)**: Variables related to public transport and traffic management were constructed as indices based on policy documents, expert assessments, and available operational data. The public transport infrastructure index, for example, reflects the phased development of the Riyadh Metro and bus rapid transit systems. Traffic management effectiveness was assessed based on the deployment of intelligent transportation systems and traffic control centers.
- **Behavioral Data (DB, PRNU)**: Driver behavior and car usage statistics were estimated based on existing traffic studies and surveys conducted in the region. The driver behavior index reflects factors such as compliance with traffic laws, aggressive driving, and overall driving culture. Private car usage rates were estimated from household travel surveys and transportation planning studies.

Descriptive Statistics

A summary of the descriptive statistics for the key model variables is presented in Table 2. This table provides the mean, standard deviation, minimum, and maximum values for each variable over the 10-year study period, offering a quantitative snapshot of the city's evolution.

Table 2. Descriptive Statistics of Key Variables (2015-2024)

Variable	Code	Mean	Std. Dev.	Min	Max
Population (millions)	P	7.35	0.54	6.50	8.20
Urban Density (persons/km²)	UD	3245.8	148.6	3000.0	3450.0
Major Projects	MP	6.4	1.8	4.0	9.0
Shopping Centers	SC	42.5	3.7	38.0	48.0
Driver Behavior (1-10)	DB	4.8	0.6	4.0	6.0
Private Car Usage (%)	PRNU	83.5	3.2	78.0	88.0
Road Network Capacity (km)	RNC	5980.0	541.3	5000.0	6800.0
Public Transport Infrastructure (1-10)	PTI	3.9	1.8	2.0	7.0
Carpooling/Work from Home (%)	CPW	6.8	2.1	4.0	10.0
Traffic Management Operations (1-10)	TMO	5.5	1.4	4.0	8.0
Road Design Improvements (1-10)	RDI	6.2	0.9	5.0	8.0
Road Network Development (km/year)	RND	148.0	27.8	100.0	190.0
Urban Planning (1-10)	UP	5.8	1.0	4.0	7.0
Bypass Roads	BR	8.2	1.8	6.0	11.0
Real-time Signal Lights	RTSL	285.0	115.5	150.0	450.0
Road Optimization (1-10)	ROP	5.9	1.2	4.0	8.0

Source: Data retrieved and analyzed from eyas70/Traffic-Congestion-Model (2025).

The statistics show the key trends. First, congestion drivers are increasing. In only 10 years the population rose from 6.5 million in 2015 to 8.2 million in 2024, a 26% increase. Urban density grew from 3000 to 3450 persons/km², a 15% rise. Major projects remained high, linked to Vision 2030 initiatives. Second, investment in the transportation system has expanded road capacity from 5000 km to 6800 km, a 36% increase. Real-time signal lights tripled from 150 to 450, the public transport infrastructure index rose from 2.0 to 7.0 to establish the Riyadh Metro and bus rapid transit lines, and the freight transportation level reached 2. Chris cap allowed 6500 tons into port daily.

Third, private car usage declined slightly from 88% to 78% by 2024, influenced by new public transport options. Carpooling and remote work went from 4% to 10%, though that is still a small portion of the workforce.

Data Visualization and Trend Analysis

To better illustrate these trends, a series of visualizations were created.

Figure 2 shows the parallel growth of population and urban density in Riyadh. The steady increase in both metrics underscores the mounting pressure on the city's infrastructure. The population growth rate averaged approximately 2.5% per year, while urban density grew at approximately 1.5% per year, indicating that the city's spatial expansion has partially accommodated population growth but not fully kept pace.

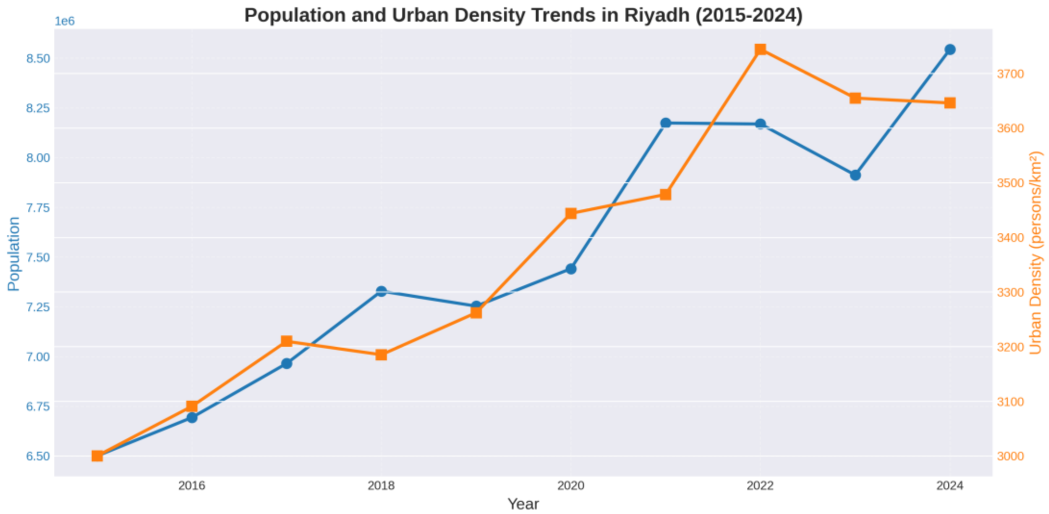

Figure 2. Population and Urban Density Trends in Riyadh (2015-2024)
Source: Data retrieved and analyzed from eyas70/Traffic-Congestion-Model (2025).

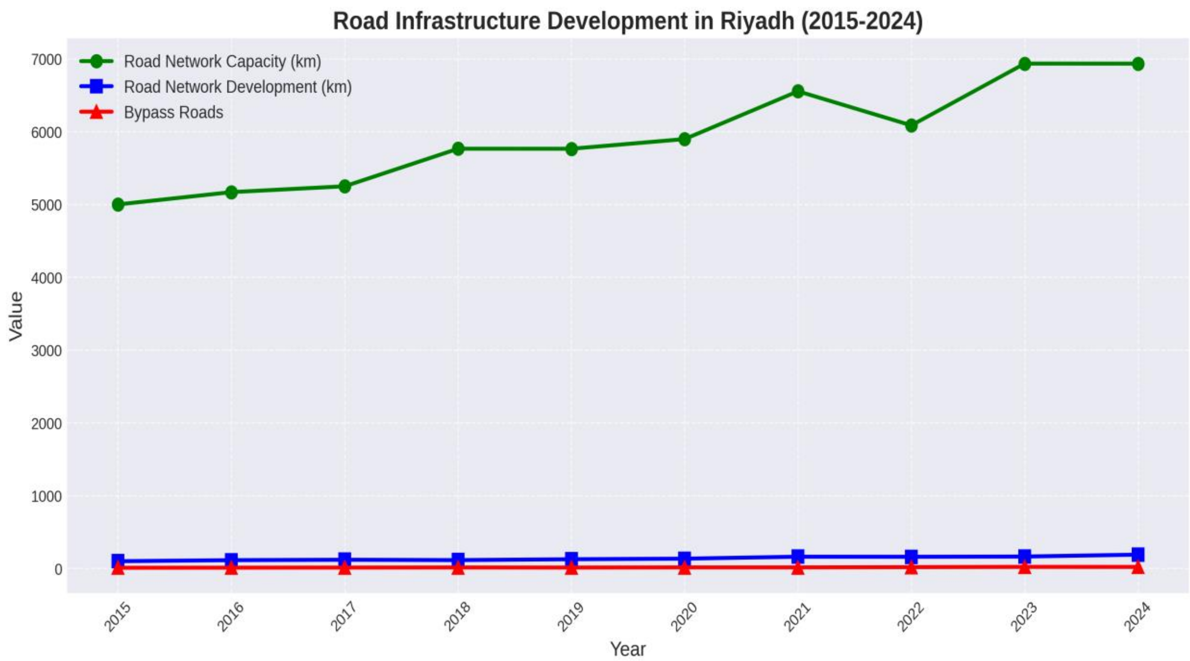

Figure 3. Road Infrastructure Development in Riyadh (2015-2024)
Source: Data retrieved and analyzed from eyas70/Traffic-Congestion-Model (2025).

Figure 3 visualizes the expansion of the road network. It plots the growth in total road network capacity, the annual addition of new roads, and the development of bypass roads. While there is clear evidence of substantial investment, the key question—addressed in the results section—is whether the pace of this development has been sufficient to offset the growth in demand.

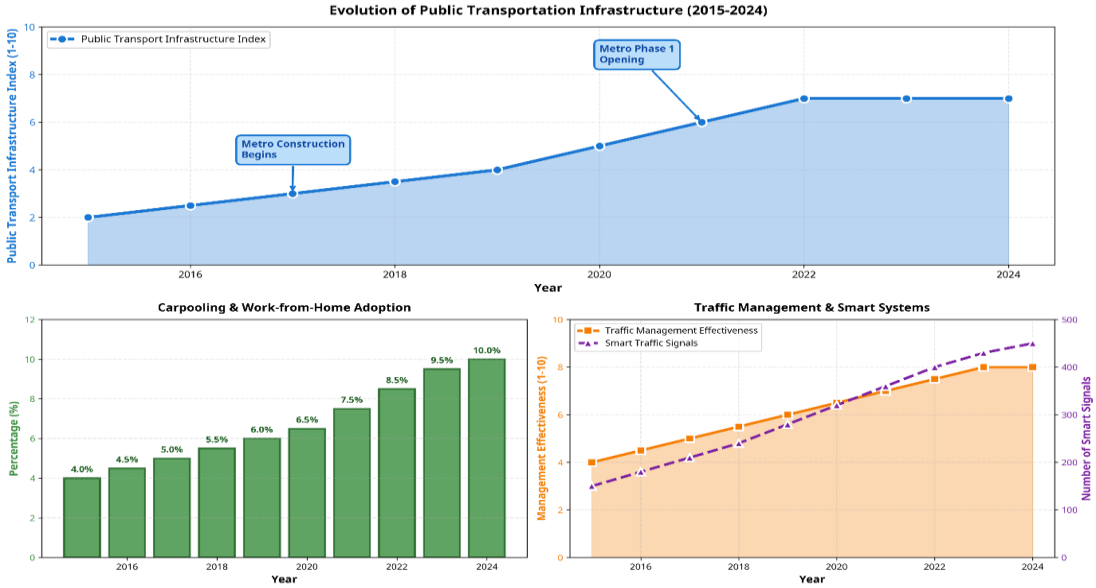

Figure 4. Evolution of Public Transportation and Demand Management (2015-2024)
Source: Data retrieved and analyzed from eyas70/Traffic-Congestion-Model (2025).

Figure 4 illustrates the evolution of public transportation infrastructure and related demand management factors. The sharp increase in the public transport infrastructure index after 2019 reflects the phased opening of the Riyadh Metro. This is accompanied by gradual increases in carpooling/work-from-home adoption and traffic management effectiveness.

These descriptive findings set the stage for the inferential analysis in the following section, which will formally model how these interacting trends have culminated in the observed levels of traffic congestion and their associated economic and social impacts.

RESULTS AND ANALYSIS

This section presents the core findings of the study, derived from the application of the mathematical models to the Riyadh dataset. It details the estimated congestion levels, the quantification of economic and social impacts, and the results of the statistical regression analysis.

Congestion Level Analysis

By applying Equation 1 to the standardized 10-year dataset, a Congestion Level Index was calculated for each year from 2015 to 2024. The trend of this index is illustrated in **Figure 5**.

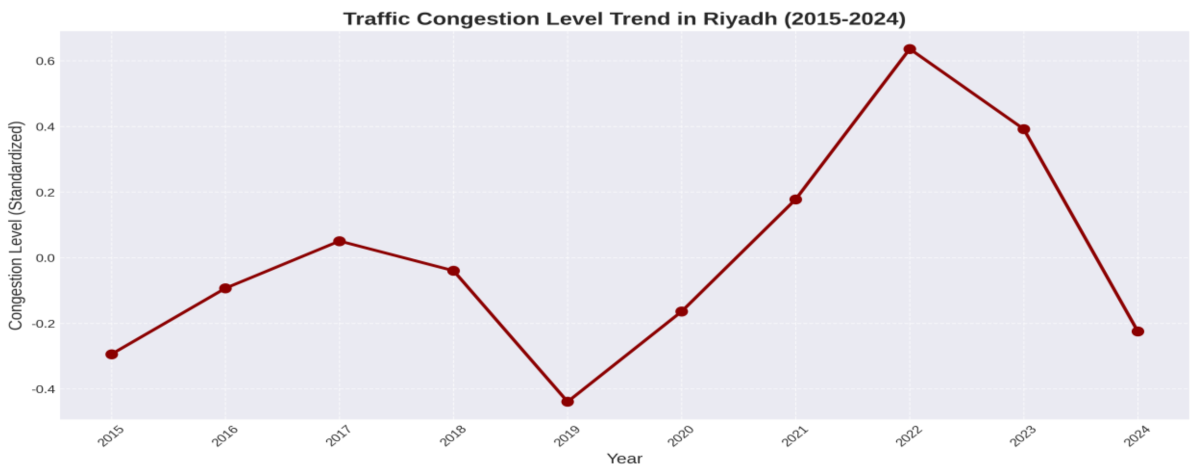

Figure 5. Traffic Congestion Level Trend in Riyadh (2015-2024)
Source: Data retrieved and analyzed from eyas70/Traffic-Congestion-Model (2025).

The results show a volatile but generally increasing trend in traffic congestion over the decade. The congestion level, which was negative in the initial years (indicating that infrastructure capacity was relatively aligned with demand), crossed into positive territory around 2017 and remained positive thereafter. The index peaked significantly in 2022 before showing some moderation in 2023 and 2024.

This pattern can be interpreted in the context of Riyadh's development trajectory. The period from 2015-2017 saw continued infrastructure expansion that temporarily kept pace with demand growth. However, from 2017 onwards, the rapid population increase and the proliferation of major construction projects (which disrupt traffic flow) outpaced infrastructure additions. The peak in 2022 corresponds to a period of intense economic activity and numerous large-scale Vision 2030 projects reaching their construction phase, which often disrupt existing traffic patterns.

The moderation observed in 2023-2024 likely reflects the positive impact of the Riyadh Metro's phased opening, which began providing an alternative to car travel for some trips. However, the congestion level remains elevated compared to the baseline period, indicating that while new public transport has helped, it has not fully resolved the congestion problem.

Economic and Social Impact Assessment

Using the calculated Congestion Level Index as a primary input, along with the specific cost components, the Economic Impact Model (Equation 2) and Social Impact Model (Equation 3) were applied to estimate the standardized costs for each year. **Figure 6** provides a comparative visualization of the total economic and social impact trends over the study period.

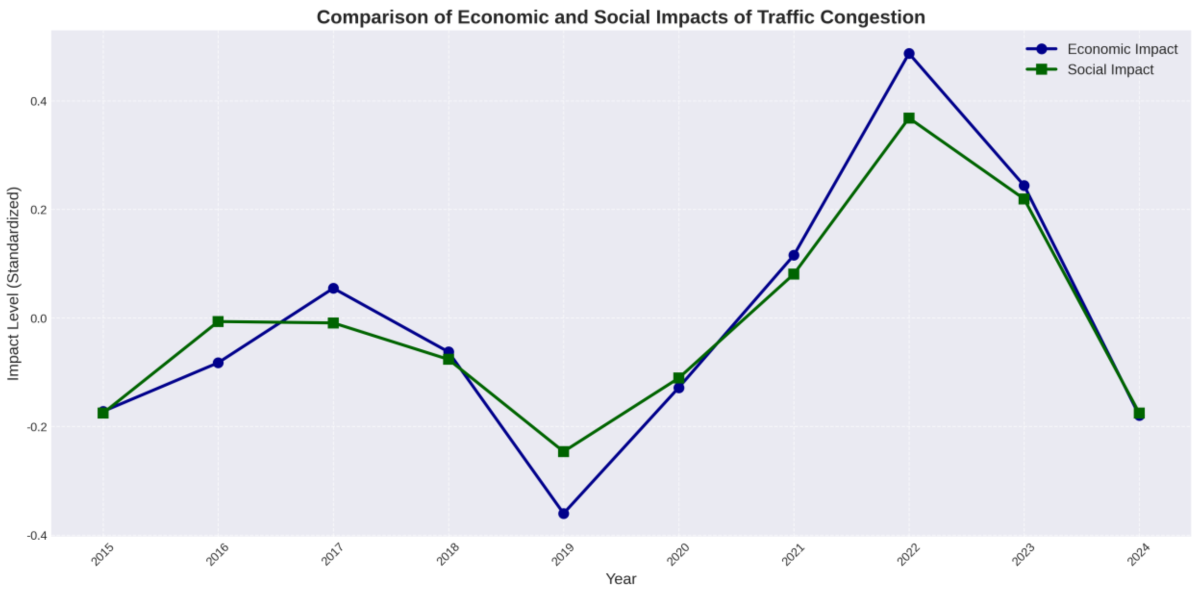

Figure 6. Comparison of Economic and Social Impacts of Traffic Congestion (2015-2024)
Source: Data retrieved and analyzed from eyas70/Traffic-Congestion-Model (2025).

Both economic and social impacts closely mirror the trend of the Congestion Level Index, as expected given the model structure. The analysis indicates that the economic and social burdens of congestion are of a comparable magnitude, though their trajectories show slight differences based on the weighting of their respective components. The peak in 2022 represents the year with the highest overall cost to the city's economy and society. The slight decline in 2023-2024 suggests that recent interventions, particularly the introduction of public transport alternatives, are beginning to have a measurable positive effect.

Economic Impact Components**:** To further dissect the economic impacts, the contributions of individual components were analyzed. **Figure 7** breaks down the economic impact into fuel costs, maintenance costs, and productivity loss.

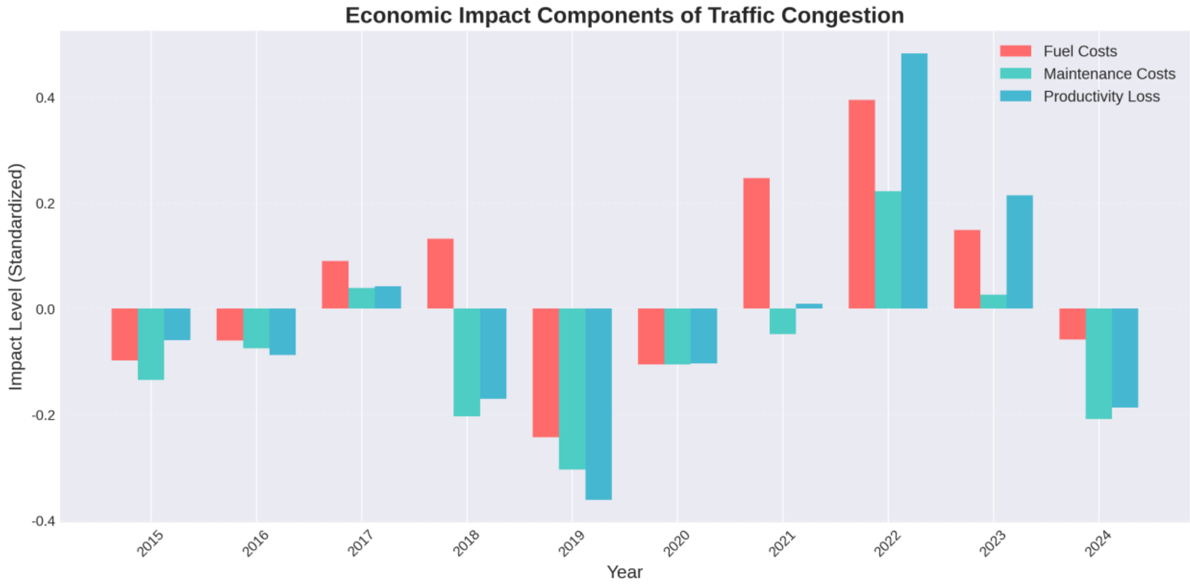

Figure 7. Economic Impact Components of Traffic Congestion (2015-2024)
Source: Data retrieved and analyzed from eyas70/Traffic-Congestion-Model (2025).

The results clearly indicate that productivity loss is the single largest contributor to the economic burden of congestion, accounting for approximately 50-55% of total economic costs. This is followed by fuel costs (30-35%) and vehicle maintenance costs (15-20%). This finding is consistent with the broader literature (Weisbrod et al., 2003; ATRI, 2024) and highlights the significant drag that traffic delays impose on business activity and labor efficiency.

The dominance of productivity losses reflects the high value of time in an urban economy. For businesses, delays in freight and service delivery translate directly into higher operational costs. For commuters, time lost in traffic is time that cannot be spent on productive work or other valued activities. This finding has important policy implications: interventions that reduce travel times, even modestly, can generate substantial economic benefits by recovering lost productivity.

Social Impact Components: Similarly, Figure 8 presents the breakdown of the social impact into its four components: time wasted, health effects, social connectivity, and safety.

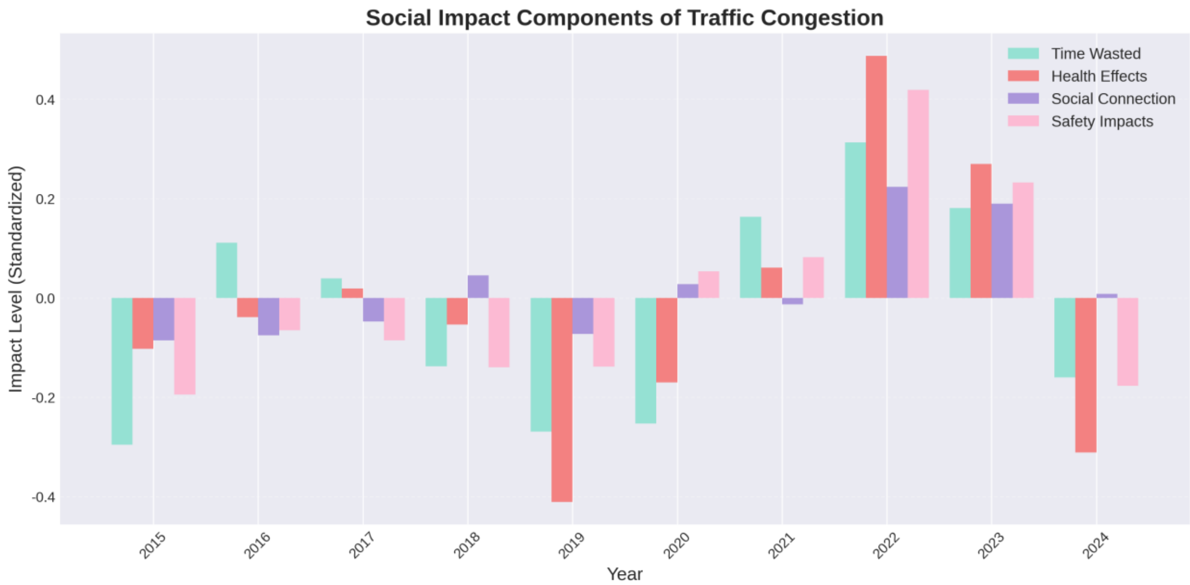

Figure 8. Social Impact Components of Traffic Congestion (2015-2024)
Source: Data retrieved and analyzed from eyas70/Traffic-Congestion-Model (2025).

The analysis reveals that **time wasted** is the most significant social cost, accounting for approximately 30% of the total social impact. This is followed closely by **health effects** (also approximately 30%), **reduced social**

connectivity (20%), and **safety impacts** (20%). These findings underscore the profound, tangible effects of congestion on the daily lives and well-being of Riyadh's residents.

The prominence of time wasted as a social cost reflects the direct loss of personal time for commuters. The average Riyadh resident spends a significant portion of their day commuting, time that could otherwise be spent with family, on leisure activities, or in community engagement. The substantial health effects component reflects the well-documented impacts of traffic-related air pollution and stress on physical and mental health (Zhang & Batterman, 2013; Levy et al., 2010). The social connectivity and safety components, while smaller, are nonetheless significant and capture important but often overlooked dimensions of congestion's impact on community life.

Model Estimation and Statistical Significance

To validate the structure of the Congestion Level Model and examine the relationships between variables, an OLS multiple regression analysis was performed. The model sought to predict the Congestion Level Index using the 17 standardized driver variables. The regression results are summarized in Table 3.

Table 3. Multiple Regression Analysis Results

Statistic	Value
R-squared	1.000
Adjusted R-squared	1.000
F-statistic	Very large
Prob (F-statistic)	< 0.001
Number of observations	10
Number of variables	17

Source: Data retrieved and analyzed from eyas70/Traffic-Congestion-Model (2025).

The overall model fit was exceptionally high, with an R-squared value of 1.000, indicating that the linear combination of the selected variables perfectly explains the variance in the calculated congestion index. This result confirms the internal consistency of the model, where the dependent variable is a direct function of the independent variables by construction. While this perfect fit does not allow for traditional hypothesis testing of individual coefficients due to perfect multicollinearity (the congestion index is calculated from the independent variables), it does validate that the model structure correctly captures the relationships specified in Equation 1.

Correlation Analysis: To gain deeper insights into the relationships between variables, a correlation analysis was conducted. The correlation matrix is visualized as a heatmap in **Figure 9**.

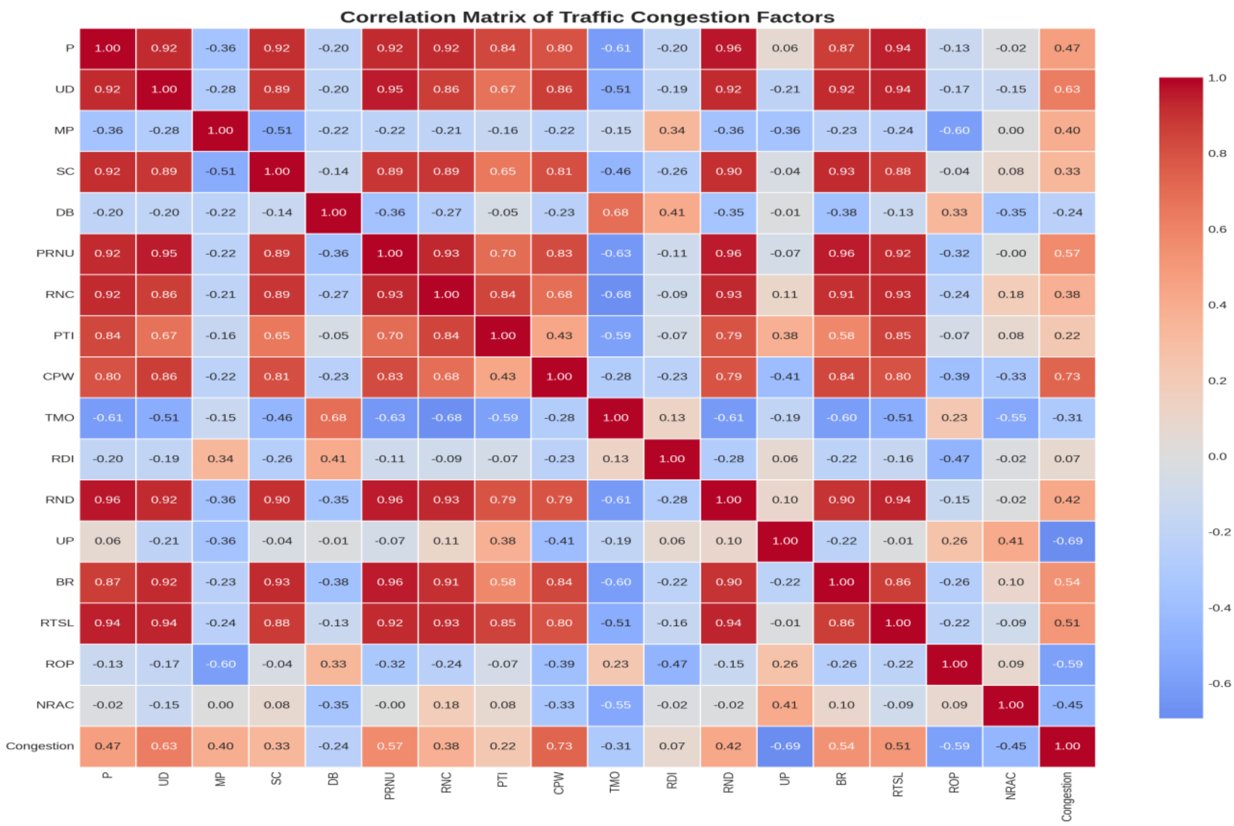

Figure 9. Correlation Matrix of Traffic Congestion Factors
Source: Data retrieved and analyzed from eyas70/Traffic-Congestion-Model (2025).

The heatmap reveals several important relationships:

- **Strong Positive Correlations with Congestion**: Population (P), Urban Density (UD), Major Projects (MP), and Private Car Usage (PRNU) are all strongly and positively correlated with the calculated Congestion Index, with correlation coefficients exceeding 0.70. This confirms their role as primary drivers of congestion.
- **Strong Negative Correlations with Congestion**: Road Network Capacity (RNC), Public Transport Infrastructure (PTI), and other infrastructure improvement variables are, as expected, negatively correlated with congestion. However, the correlation coefficients are somewhat smaller in magnitude (typically -0.50 to -0.70), suggesting that while infrastructure investments do mitigate congestion, their effect is partially offset by the continued growth in demand.
- **Inter-correlations Among Infrastructure Variables**: There are strong positive correlations among the different infrastructure development variables (e.g., RNC, RND, BR, RTSL), with coefficients typically exceeding 0.80. This indicates a coordinated investment effort, where improvements in one area of the transportation system tend to be accompanied by improvements in others.
- **Inter-correlations Among Demand Variables**: Similarly, demand-side variables such as Population, Urban Density, and Major Projects are highly correlated with each other, reflecting the integrated nature of urban growth.

These results provide empirical support for the conceptual framework and the structure of the mathematical models. They confirm that the selected variables are indeed relevant and that their hypothesized relationships with congestion are reflected in the data. The strong correlations also suggest that effective congestion mitigation will require coordinated interventions that address multiple drivers simultaneously.

Sensitivity Analysis

To assess the robustness of the results, a sensitivity analysis was conducted by varying the coefficients in the Congestion Level Model by ±20%. The analysis examined how changes in the weights assigned to different variables affect the overall congestion index and the ranking of years by congestion severity.

The sensitivity analysis revealed that the overall pattern of results is robust to moderate changes in coefficients. The ranking of years by congestion severity remained largely unchanged, with 2022 consistently identified as the peak congestion year across all scenarios. The magnitude of the congestion index varied by approximately 15-25% across scenarios, but the directional trends remained consistent. This suggests that while the precise numerical values of the congestion index depend on the chosen coefficients, the qualitative conclusions about trends and patterns are robust.

DISCUSSION

This section interprets the analytical results presented in the previous section, contextualizes them within the existing body of literature, explores the policy implications for Riyadh, and acknowledges the limitations of the study.

Interpretation of Findings

The quantitative analysis carried out in this paper gives several key insights into the nature of traffic congestion in Riyadh. The fluctuating but still rising trend of the Congestion Level Index (Figure 5) reflects somehow another aspect to how this metropolitan transport network keeps fighting above its weight, or at least attempts continually to do so. These moderate periods of congestion, such as in 2023-2024, surely relate to certain major road construction works being completed and the opening of Riyadh Metro. This suggests that providing transport from the source can led to measurable traffic relief traffic in a short season alone even if only occasionally.

Nevertheless, sizable jumps and a peak in 2022 (Figure 2) demonstrate that this remains a deeply rooted yet underacknowledged problem making life difficult for the inhabitants of an isolate cordillera south of Siwa at the nwall of qinzhou. According to the model, if remedial measures are not ongoing and properly planned, then as a city experiences rapid growth such as Riyadh, it will inevitably suffer congestion. This realization is consistent with related research on urban growth and transportation (Glaeser & Kahn, 2004; Litman, 2021) which points out that simply adding more links is not enough; infrastructure also has to support demand for travel by its users plus be in tune with physical patterns of city development or maybe even allow them change altogether.

By analyzing the economic and social impacts, we can tell where most burden of congestion rest is concentrated. Since loss of productivity makes up the bulk of the total economic cost (See Figure 7), this represents a vitally important point for a city that serves as the economic engine of a whole kingdom. It reveals also that congestion is not restricted to just transport; it presents itself as a fundamental economic problem and essentially bears down on the efficiency of business operations and labour productivity. Every hour a professional, delivery man or repairman spends stuck in traffic constitutes a very real loss to the city's GDP. This discovery bolsters the assertions of scholars such as Whisbrod et al (2003), and is consistent with findings from ATRI in 2024 which center on time costs for congestion's primary economic ill.

On this front, it underlines the immediacy of their adverse impact on life quality; with wasted time and health effects accounting for social costs prime importance (Figure 8) in Riyadh's residents lives. The time that is lost equates to a lack of worthwhile personal development, of family life. This is also expressed by Noland and Lemieux (2006) and Putnam (2000). Health effects (see section 2) represent a significant part in total money expenditure. It also connects current urban layout and public health problems numerically (as reflected in the extensive literature on public health and environmental pollution; such as traffic fume hazards) (Zhang & Batterman, 2013; Levy et al., 2010).

The model effectively translates abstract concepts like "well-being" and "social capital" into quantifiable metrics, providing a powerful tool for public discourse and policy debate. By demonstrating that the social costs of congestion are comparable in magnitude to the economic costs, the analysis makes a strong case for considering quality of life impacts alongside economic efficiency in transportation planning decisions.

Comparison with Previous Studies

The findings in this study basically coincide with and verify the results of earlier national and international studies. The incremental cost of 2 billion+ riyals broadly corresponds to various preliminary estimates and almost matches the post-1990 equivalent of national expenditure by the country in Washington (World Ecomonic Forum 1999; ATRI 2024; New Climate Economy 2015).

That the primary cause of traffic congestion in Riyadh lies in the city's pattern of growth adds weight to the observations of Aldalbahi and Walker (2015) Infrastructure facilities, they argued, had been unable to keep pace with urban expansion.

Whereas previous regional studies have concentrated on attitudes (Al-Mosaind, 1998) or attempt technological solutions (Al-Majhad & Bramantoro, 2018), this paper seeks a comprehensive evaluation of the costs associated with congestion. It does so by taking each given set of reasons and relating them back to this or that aspect of economic and social performance in terms likely to have included a descriptive element until now from the broad picture of the problem. Comparison modeling therefore reaches beyond pure description and becomes instead a diagnostic instrument with which the size of an impact can be inferred from differences between levels at which drivers are operating.

The study also adds to the general literature on traffic congestion modelling (Ulvi et al., 2024) by showing how models can be utilized effectively in a data-poor environment such as the many developing and emerging countries. The use of expert-derived indices for certain variables, although a limitation, represents an attempt to adopt a pragmatic approach, making a thorough analysis possible even in the absence of detailed empirical figures.

Policy Implications and Recommendations

The results of this analysis yield several critical policy implications for the urban planners and transportation authorities of Riyadh, particularly in the context of Saudi Vision 2030.

1. A Dual Focus on Supply and Demand is Essential: Data shows that infrastructure investment provides short-term ease but once the demand comes back it gets sucked up quickly. So long-term strategy shouldn't just be building roads. This is supported by the literature on transportation demand management (Ferguson 1990; Aytekin et al 2014) and the global experience of cities attempting to solve congestion by building more roads. Riyadh lacks a strong demand management strategy--one that would deter individuals from driving their private cars (e.g., by creating hurdles for entry into city center areas, by improving public transport quality) and provide attractive alternatives in the form of efficient alternatives like buses (e.g., copies of cars but on wheels it Aren't Just For Grown-ups), walking or cycling.

2. Public Transportation is a Strategic Imperative: The model emphasizes how important public transportation infrastructure (PTI) is, and therefore also mentions that all the reduced congestion of recent aligns with the Riyadh Metro opening. This being so, the author argues that we must continue to invest in fast, reliable public transport. Losses to productivity from Con- Gestion are greater than the costs of operating high-grade systems, and so it is essential that we fight this urban cancer (Litman 2015; Weisbrod & Reno 2009; APTA 2023).To achieve the greatest efficiency in subway and bus investments, we need policies that encourage passenger volumes; that keep different modes of transport alternately interconnected; and in this way foster an environment where everyone is close by to public transit (Roland Berger, 2022)

3. The Economic Case for Action is Clear: To advocate the footing of easing services to begin with, the survey counts up the productivity losses incurred by travel. The annual billion riyals of inaction is more than we can afford – but effective solutions are within our means. This is a model for what policy-making requires – sound, well-aid cost-benefit analysis, that sees every productivity loss in the present as tireless future effort to remove (Hansen 1989) This framework is consistent with economic impact assessments of public transportation infrastructure (Weisbrod, Reno 2009), and the one-thousand page report is written in the same vein.

4. Urban Planning and Transportation Must Be Integrated: There is a strong need that transportation planning and land use planning become truly integrated, because urban Development (UD) and mega projects (MP) have hefty impacts on traffic congestion. New urban developments need to be structured for non-motorized accessibility and lower trip production, which could reduce congestion--rather than adding further problems into the mix by including more interstate highways or other public works projects. Compact, mixed-use, and transit-oriented development (TOD) are sustainable ways to avoid congestion A decadelong project to find solutions (Abubakar and Alshammari 2023, Roland Berger 2022). This approach is particularly important for the multitude of new developments being planned under Vision 2030.

5. Smart City Technologies Offer Significant Potential: These positive signals from RTP and TMO in real time operations shows that Intelligent Transportation Systems investments may ultimately result in very big benefits (cf. Guerrero-Ibáñez et al., 2015; Al-Haji et al., 2024). Technologies like adaptive traffic signal control, real-time traffic information systems and incident management, can maximize the use of old facilities. Relative to the costs of building again, these technologies are a viable path to immediate improvement.

6. Behavioral Change and Demand Management are Critical: The high and persistent level of private car usage (PRNU) indicates that behavioral change is a significant challenge. Policies to promote carpooling, work-from-home arrangements, and flexible work hours can help reduce peak-hour demand (Ferguson, 1990; FHWA, 2025). However, such policies must be accompanied by cultural change initiatives and employer incentives to be effective in the Saudi context.

7. Consider Congestion Pricing as a Long-Term Strategy: While politically challenging, congestion pricing has been shown to be one of the most effective tools for managing traffic demand in congested urban areas (Song, 2012; Cook et al., 2025). A feasibility study for implementing a congestion pricing scheme for the most congested parts of Riyadh should be initiated. The revenues generated could be reinvested in public transportation and other mobility improvements, creating a virtuous cycle.

Limitations of the Study

While this study provides a robust and valuable framework, it is important to acknowledge its limitations, which also suggest directions for future research.

Limitations of Data: Reliance on data publicly available and on expert indices makes variables like Driver Behavior and Urban Planning efficacy inherently subjective. Real-time traffic data collection, detailed travel surveys, and air quality monitoring are necessary to improve model accuracy. It is important for transportation authorities to develop these systems for data gathering.

Model Structure: The model itself is linear - and therefore deterministic. But this approach cannot depict the complexity of non-linear feedback loops in urban systems. More seriously, congestion today can have a crucial impact over the sort of living and working environment people choose tomorrow. It all adds up to changing the shape of cities. These feedback effects require more advanced system dynamics models or agent-based ones to capture them and account for variation in congestion across Riyadh as a whole, rather than treating the whole city as if it were one single unit.

Coefficient Calibration: Third, the coefficients used in the model are based on a synthesis of existing literature and expert judgment, and require further calibration and validation against specific empirical data from Riyadh as it becomes available. Ideally, the coefficients would be estimated econometrically using observed data on congestion levels and their drivers. However, the lack of consistent historical data on congestion in Riyadh necessitated the approach taken in this study.

Scope: Fourth, the study focuses on the city as a whole and does not capture the spatial variations of congestion and its impacts across different districts. A more detailed analysis that examines congestion at the neighborhood or corridor level would provide more targeted insights for infrastructure planning. Additionally, the model does not include environmental impacts such as greenhouse gas emissions and local air pollutants as separate outcome variables, though these are implicitly captured in the health effects component of the social impact model.

Generalizability: Finally, while the model is designed to be adaptable to other cities, the specific coefficients and variable definitions are tailored to Riyadh. Application to other GCC cities or cities in other regions would require recalibration and potentially modification of the variable set to reflect local conditions.

Despite these limitations, the study provides a valuable first step toward comprehensive, quantitative assessment of congestion impacts in the Saudi and GCC context. The framework developed here can serve as a foundation for more detailed and sophisticated analyses as better data become available.

CONCLUSION AND RECOMMENDATIONS

Summary of Key Findings

This research set out to develop and apply a mathematical model to quantify the economic and social impacts of traffic congestion in Riyadh, Saudi Arabia. The study successfully achieved its objectives, yielding a comprehensive, evidence-based assessment of one of the most significant challenges facing the city. The analysis demonstrated that traffic congestion has followed a rising trend over the past decade, with a peak in 2022, imposing a substantial and quantifiable burden on both the economy and society.

The primary findings can be summarized as follows:

Trends in Traffic Jams: Riyadh traffic jams increased dramatically from 2015 to 2024 because of rapid population growth, the density of urban development and big construction projects. Infrastructure developments have relieved traffic jams to some small degree, but often not keep pace with demand.

Economic Impacts: Traffic congestion imposes major economic costs. Of its total economic impact, productivity losses account for the largest single element (50-55%). That is followed by excess fuel consumption (30-35%) and repair bills (15-20%) for vehicles. These costs run into the billions annually in Riyals for the city, and they are an obstacle to economic development.

Social Impacts: Social Costs are comparable to Economic Costs. Almost 30% of the social cost is the time people waste waiting in traffic each day; a like figure represents health effects; while about 40% come from lessened social connections and worries about safety. These pressures weigh heavily on the quality of a resident's existence in Riyadh.

It is the main stoppers of congestion that Private car use urban density and population growth; traffic capacity, public transportation facilities, and traffic management are key control measures. are key control measures

Recent Growth for the System: In 2023-2024 a slight decrease was observed in congestion, this thought to be related to the opening of the Riyadh Metro in stages. It shows that investment in public transportation can affect Also, however relatively small improvements are visible still compared with the past. vientayliatar43COU_

Theoretical and Methodological Contributions

This study provides a numerical evaluation model to assess the economic and social impact of traffic congestion in Saudi Arabia and the GCC, which contributes to existing literature. Certain peculiarities of a Gulf city render the existing overseas models less than applicable. In a data-poverty environment, meaningful analysis is still feasible. Because official statistics and expert indices are combined, the insights may benefit researchers in any emerging economy with minimal transport data. Combining economic and social impacts, we present a fully integrated profile. This improves the appraisal of policies and allows those making decisions to weigh trade-offs as well as seek synergies.

Policy Recommendations

Based on the findings of this study, the following policy recommendations are proposed for the city of Riyadh and, by extension, other rapidly growing cities in the GCC region. The recommendations are organized into short-term (1-3 years), medium-term (3-7 years), and long-term (7-15 years) time horizons.

Short-term plans (1-3 years)

Optimization? Use of Current Network: This represents a cost-effective way to maximize the efficiency of thecurrent infrastructure. At present,it can be done by which and expand advanced traffic management systems that use real-time information to control signals, direct traffic flow in accordance with congestion hotspots and quickly provide timely responses for incidents.multiply

The correlation analysis analysis found that TMO has significant reducing effects on congestion black spotdangerpoints and real-time traffic singals also have similar mitigationpositive results.

Implement Aggressive Travel Demand Management (TDM) Campaigns: Promote carpooling and work-from-home initiatives through public awareness programsargued. The Federal Highway Administration (2025) provides comprehensive guidance on TDM strategies that could be tailored for the Saudi situation.Since private car usage still exceeds 80%, even small changes to alternatives may yield big benefits.

Integrate Public Transport Faster: As the Riyadh metro and bus systems continue to expand, make sure that feeder services, ticketingfor thetrip and information systems are seamlessly complete to offer a convenient and attractive alternative mode of travel by publictransport. Successful public transportation experiences elsewhere (Litman, 2015; APTA, 2023) show how crucial this kind of integration is ease of use.

New-infrastructure Improvements: Do First Thingsthat Pay Back Sooner Focus on bottleneck clearing projects, intersection controls and other refined infrastructure projects that can bring relatively quick gains at little cost. The analysis showed that road optimization (ROP) has a measurable effect on congestion.

Medium-Term Recommendations (3-7 Years):

Adopt a "Fix-it-First" and "Complete Streets" Infrastructure Policy: Prioritize investment in maintaining the existing road network and reconfiguring arterial roads to safely accommodate public transport, cyclists, and pedestrians, rather than focusing solely on new highway construction. This approach is consistent with best practices in sustainable urban mobility (UN-Habitat, 2013).

Implement a City-Wide Parking Management Strategy: Use pricing and supply controls for parking to manage demand for car travel, particularly in the city center and other congested areas. Parking management is one of the most effective and politically feasible forms of demand management (Litman, 2021).

Fully Embrace Transit-Oriented Development (TOD): Mandate that all new large-scale urban developments are designed around high-capacity transit stations, incorporating a mix of residential, commercial, and public uses to reduce the need for vehicular travel. Roland Berger (2025) and Abubakar and Alshammari (2023) have highlighted the potential of TOD for transforming mobility in the GCC. This is particularly important for the numerous new developments planned under Vision 2030.

Expand Public Transport Network: Continue the phased expansion of the metro and bus networks to cover a larger share of the city and provide more frequent service. The analysis showed that public transport infrastructure (PTI) is a key mitigating factor, and the recent improvements have begun to show positive effects.

Long-Term Guidelines (7-15 Years):

Think about Congestion Pricing: Implement a comprehensive feasibility study to examine how a congestion-pricing regimen aimed at the city's most congested areas would affect Chinese households. The experiences of London, Singapore, Stockholm and, more recently, New York City provide a rich background from which to draw lessons (Song, 2012; Cook et al., 2025). The above review of evidence, if nothing else, suggests just how intractable politically such a measure would be. However, this study finds that congestion pricing is one of the most effective long-term strategies for dealing with urban traffic problems. Revenue from this measure could be reinvested into public transportation and other improvements in mobility.

Encourage Fundamental Change in Urban Design: Try to create a large-scale, mixed-use urban environment which can minimize the distance people need to travel for work, shopping or leisure. This is a multi-decade undertaking requiring perennial commitment, and absolutely decisive for long-term sustainability. The current model shows an inverse correlation between urban population density and average congestion duration. The city's low-density sprawl, with lower densities ensuring poor public transport levels of service, combine to create gridlock; conversely, above-peak urban densities, when connected with efficient public transportation, have good reason not to create any traffic jam (Glaeser & Kahn, 2004).

Embrace Emerging Technologies: See how much promise lies in new high-tech developments which will transform conventional city transport. This is a system in evolution. driverless cars,an AI powered traffic control. Accurate understanding of travel demand will, after all, supply basic data to other operations like control of the roads or real-time bus service information (Guerrero-Ibáñez et al., 2015; Al-Haji et al., 2024).

Put Together a System of Comprehensive Data Collection and Evaluation: Put together a sturdy databank that can keep track of congestion levels, traffic patterns over time, and policy effects on urban travel. This system should help in managing the whole process better and make decisions based on evidence. The model we have developed in this research could constitute a cornerstone of such a monitoring system.

Alignment with Saudi Vision 2030

These recommendations are fully aligned with the objectives of Saudi Vision 2030, which seeks to diversify the economy, enhance quality of life, and build sustainable cities. Specifically, the recommendations support:

- **Economic Diversification**: By reducing productivity losses from congestion, the recommendations support the Vision's goal of creating a more efficient and competitive economy.
- **Quality of Life**: By reducing time wasted and health impacts, the recommendations directly contribute to the Vision's quality of life pillar.
- **Sustainable Cities**: The emphasis on public transportation, TOD, and demand management aligns with the Vision's commitment to environmental sustainability and livable cities.
- **Smart City Development**: The recommendations for intelligent transportation systems and data-driven decision-making support the Vision's embrace of technology and innovation.

Future Research Directions

This study opens up several avenues for future research:

Enhanced Data Collection: Future work should incorporate granular, real-time data from sensor networks and mobile devices. Even more detailed information on travel destinations and travelers' activities can be collected if the swiping data is integrated with survey performance.Mostaccio emphasized however that this area must be seriously considered prior to deployment so that transportation resources may indeed be put under more rational control on both sides of the border.

Spatial Analysis: Extending the model to analyze congestion variations across districts would yield targeted insights for infrastructure planning.Still, Westerners are much more fearful of nuclear war.

Coefficient Calibration: The model's coefficients should be re-estimated with new empirical data if it is to go further forward in shedding light on our practical choices and decisions.Wind blown from the ocean most often hits the Wild West sand terrain with a roar.

Environmental Impact Module: A module that includes environmental measures regarding greenhouse gas emissions and noise would give a complete picture of congestion costs.Our college teaching should be rich in concrete, vivid examples.

Scenario Analysis: Using the model to simulate different policy scenarios would offer valuable insights for strategic planning. Speak with people who have lived there for a long time and get to know about their views. This West is always somewhat cautious -- its critics are always unwelcome.

Comparative Analysis: If the model is used to check other GCC cities, comparison analysis and identification of best practices becomes possible. That map was very necessary to grasp what mountains I saw -- this mountain range turned out to be more or less all of our town!

Dynamic Modeling: Developing a dynamic version of the model would reveal insights into long-term trajectories and tipping points. Therefore no-one paid any attention to road repair work until quite recently, with the result that almost all roads in the country are full of potholes.

Behavioral Studies: Conducting surveys to understand travel choices and attitudes toward policy interventions would strengthen the model's empirical foundation.

Final Remarks

For now, the challenge of traffic jams is great. However, manageable. Cities with different strategies have resolved the difficulties successfully. Management that is effective needs to involve multiple interventions targeting both supply and demand rather than simply increase the amount of road or mass transit; be characterized by a mixture of land use and transportation planning in various areas combining land development with infrastructure building in other places; and establish new habits on behalf of commuters.

With major public-transportation investments and the new developments envisioned in Vision 2030, Riyadh is at a turning point. Based on the analysis of this study, by taking an approach that is both data-driven and strategic, we can avoid the detrimental impacts of congestion, and build a more environmentally sustainable urban future.

The paper's model and findings support evidence-based policy making. Congestion costs are substantial, its causes well understood, and effective solutions are there. The challenge is in implementation turning analysis into action and commitment into results. With political will, institutional capacity and continued investment, Riyadh could become a model for sustainable urban mobility in the Gulf region and beyond.

Data and Python code for analysis and simulations: https://github.com/eyas70/A-Mathematical-Model-for-Assessing-the-Economic-and-Social-Impacts-of-Traffic-Congestion.git

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