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Establishing a Comprehensive Spatial Data Framework to Support Road Design and Maintenance Activities Using GIS and Open Source Data

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ABSTRACT This study aims to establish a Comprehensive Spatial Data Framework (CSDF) utilizing GIS and road design software to enhance road design activities in Jazan City, aligning with the Kingdom's Vision 2030. The CSDF consists of soil tests, road design, and cost estimation. AutoCAD Civil 3D is employed for road geometric design in accordance with the American Association of State Highway and Transportation Officials (AASHTO) standards and the Saudi code. The CSDF model for the Jazan road network is developed using ArcGIS 10.4. This study focuses on the Alshawajra Road, which connects University Road with Alshawajra Road. The road spans 1000 meters in length and is 28 meters wide. The methodology outlined in this paper consists of four sections: the first discusses the literature review and road design principles; the second emphasizes the survey data required; the third addresses soil collection for testing, including California Bearing Ratio (CBR), Standard Proctor, and sieve analysis. The final section covers the design of the road network and the creation of a geodatabase. The findings indicate that the third version of the proposed design is the most effective, with the total construction cost amounting to 1,233,706.17 Saudi Riyals. Additionally, the CSDF model for Jazan city roads was established, which is vital for the simplicity of data recording and updating, serving as a reference for infrastructure planning and maintenance.

INDEX TERMS Comprehensive Spatial Data Framework (CSDF), Geometric Design, Pavement Design, Geographic Information Systems (GIS), Building Geo-database, Soil Tests.

I. INTRODUCTION

A. COMPREHENSIVE SPATIAL DATA FRAMEWORK TO SUPPORT ROAD DESIGN ACTIVITIES

The primary objective of this study is to create a Comprehensive Spatial Data Framework (CSDF) to assist in the road design and maintenance efforts of Jazan City. Establishing a robust spatial data foundation for road design is essential for improving urban infrastructure and planning in Jazan City. By utilizing GIS and advanced analytical techniques, urban planners can make better judgments that enhance road safety, efficiency, and sustainability. The ongoing trend of urbanization presents unprecedented challenges for highway construction[1-2]. Constructing roads and vital connections between cities requires navigating complex terrains, coordinating various transportation modes, and managing significant land. [3].Traditional project management approaches often exacerbate coordination issues in planning, design, and construction, leading to excessive costs, information silos, and communication barriers. It is noteworthy that most existing roadway infrastructure is documented in 2D drawings, lacking 3D interactivity and advanced analytical tools, which leads to fragmented data and ineffective communication [4]. Therefore, establishing a comprehensive spatial data framework for road design and maintenance using GIS and open-source data is a critical area of research. Several studies have contributed valuable insights into how GIS technologies can enhance road infrastructure management. One notable study developed a comprehensive framework for highway maintenance planning using GIS.

This research demonstrated that spatial data visualization significantly aids decision-making processes, enabling planners to identify maintenance needs and prioritize projects effectively [5].

Another investigation integrated GIS with machine learning algorithms to optimize road maintenance strategies, highlighting the potential of combining spatial data with predictive analytics to assess road conditions and allocate resources more efficiently, ultimately improving maintenance outcomes [6]. Additionally, research by Martinez et al. (2019) [7]examined the use of open-source GIS tools for asset management in road networks, illustrating how these tools facilitate data collection and analysis, enabling better tracking of road conditions and maintenance activities. This approach supports the establishment of a more responsive and adaptive maintenance framework. Furthermore, a study conducted by Chen et al. (2022) [8] explored the application of GIS in sustainable road design, emphasizing the importance of integrating environmental considerations into road planning and maintenance. These studies collectively underscore the critical role of GIS and open-source data in developing effective frameworks for road design and maintenance, offering valuable methodologies and insights for future research and practice.

B. GEOMETRIC DESIGN AND STRUCTURAL DESIGN OF ROADS

The geometric elements of roadway design are essential for assessing traffic operational efficiency [9]. Key components of geometric design that influence traffic operations include the number and width of lanes, the presence and dimensions of shoulders and medians, as well as the horizontal and vertical alignment of the highway. Most drivers are able to travel safely at their preferred speed throughout the alignment when there is consistency in alignment. However, while the current design speed-based alignment standards allow for this, most drivers' desired speeds can vary [9]. The goal of road design is to 8. construct a safe and efficient roadway that meets the demands of its users [10,11]. Road design involves planning and laying out the physical aspects of a road, including its Width, alignment, curvature, and grade [12]. Premature road failures, manifesting as cracks, surface wear, and irreversible deformations, are common issues with flexible pavements [13]. The main causes of these failures in asphalt concrete mixtures include increasing traffic volumes, heavy vehicle loads, high tire pressures, rising temperatures, and the use of poor-quality materials and inappropriate asphalt mix designs [14].

C. BUILDING A GEO-DATABASE OF DESCRIPTIVE DATA ABOUT JAZAN ROADS NETWORK USING ARCGIS 10.4

The geodatabase is a fundamental component of GIS. Geodatabases are typically organized using broad data types, such as land base, transportation, environment, and utility infrastructure. They utilize effective spatial indexing to continuously record an extent. Personal geodatabase datasets can represent small and medium-sized enterprises [15]. Users can dynamically model realistic network conditions, such as turn restrictions, speed limits, height restrictions, and traffic conditions at different times of the day using ArcGIS 10.4 Network Analyst [16]. ArcGIS 10.4 has proven to be one of the most efficient, productive, and time-saving tools for transportation planning and traffic engineering[17]. This study outlines the steps taken to build a geo-database of Jazan roads:

a) Choose the GIS program: ArcGIS 10.4 and QGIS 3.24.2;
b) Create a spatial database that efficiently manages and arranges the data;
c) Design the database to ensure easy access, analysis, and visualization of road information;
d) Transform collected data into common GIS-compatible formats (such shape files);
e) Integrate various information (such as environmental factors, land use, and transportation statistics) into a single GIS database; and
f) Update the Road Spatial Data Framework monthly and annually to meet the emergency tasks of the Jazan road network.

D. INTELLIGENT TRANSPORTATION SYSTEMS (ITS) AND GEOGRAPHIC INFORMATION SYSTEMS (GIS)

The intersection of Intelligent Transportation Systems (ITS) and Geographic Information Systems (GIS) represents a specialized area of research and application aimed at optimizing transportation networks through the use of spatial data and technology. This study focuses on the specializations of ITS within the CSDF using GIS and open-source data. These specializations include:

☒ **Traffic Monitoring and Control**

This area applies GIS to track and analyze traffic behavior, leveraging spatial data to understand congestion trends. Real-time monitoring facilitates adaptive traffic control measures that enhance flow and reduce delays.

☒ **Route Planning and Navigation**

GIS tools play a vital role in planning optimal routes by analyzing geographical features and current traffic conditions, enhancing navigation systems to be more responsive to real-time changes.

☒ **Smart Transportation Systems**

The integration of GIS in smart transportation initiatives enables real-time data sharing between vehicles and infrastructure, enhancing overall system responsiveness and efficiency.

☒ **Safety Analysis**

The application of GIS in analyzing accident data helps information is crucial for developing targeted safety measures and interventions [18,19].

The primary objective of this paper is to integrate soil laboratory testing, manual design, AutoCAD Civil 3D, road geometric design, pavement design, traffic studies, cost estimation, and geodatabase establishment in Jazan City, in accordance with the requirements of the American Association of State Highway and Transportation Officials (AASHTO). Additionally, this model is utilized for maintenance. The secondary objectives are as follows: to employ engineering concepts to create a road that is both safe and efficient; to consider environmental factors in road design;

a. To establish a Comprehensive Spatial Data Framework (CSDF)was established to support road design and the geodatabase model for routine maintenance using GIS and open-source data.
b. To identify and engage relevant parties such as municipal authorities, transportation planners, civil engineers, and local communities, to gather source software (AutoCAD civil 3D);
c. To compare volume calculation methods;
d. To calculate the cost estimation of earthwork and pavement volumes;
e. To integrate the Comprehensive Spatial Data Framework (CSDF)and open source data within a Geographic Information System (GIS) environment to support road design and traffic analysis of the study area;
f. To propose Intelligent Transportation Systems (ITS) to improve traffic management.

II. MATERIALS AND METHODS

The methodology is described in the following steps:

A.THE FIELD OF STUDY

Figure 1 below illustrates the location of the study area. Jazan Road, which connects University Road and Alshawajrah Road, was selected as the route for the case study. The road is one kilometer long, twenty-eight meters wide, and has an average elevation of 9.799 meters above mean sea level (Jazan datum).

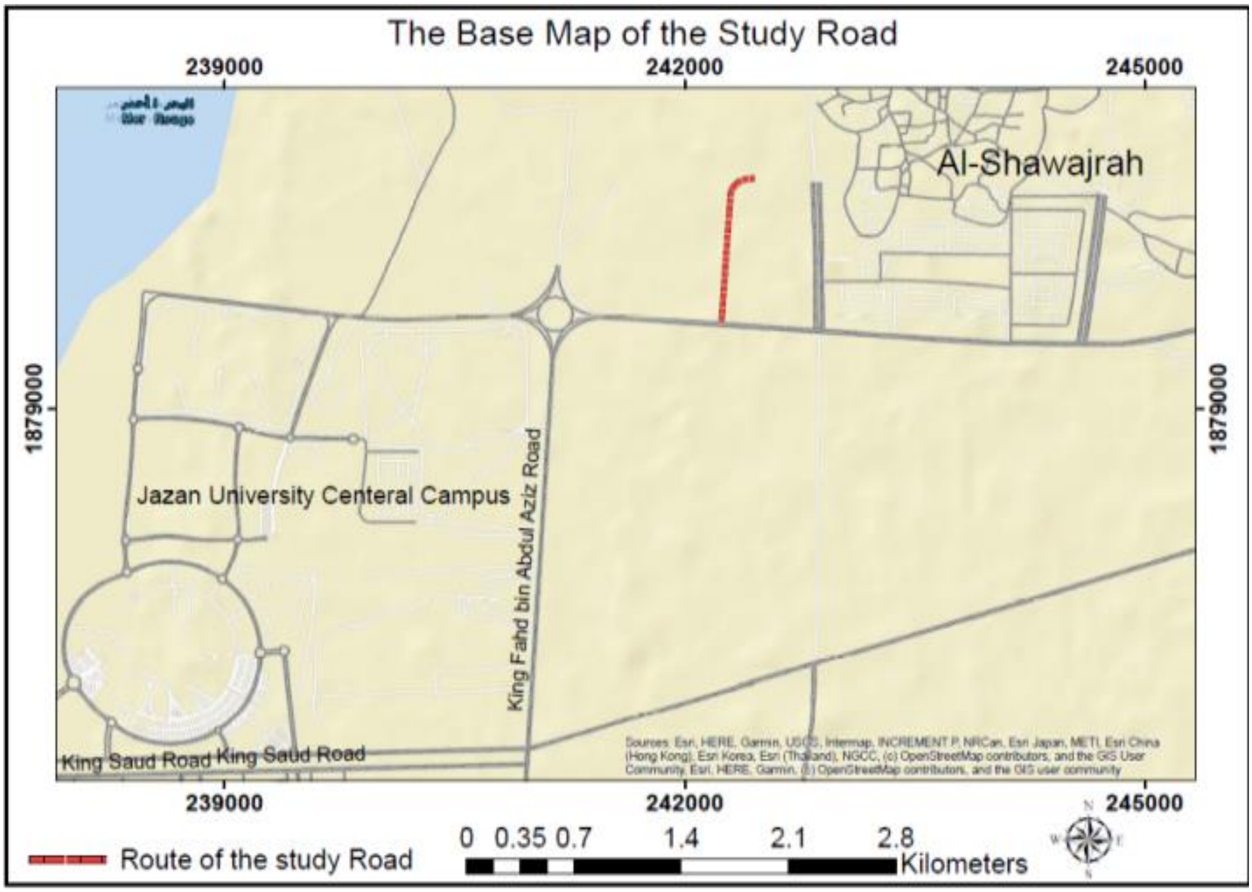

FIGURE 1.The base map of the study road

B.PAPER METHODOLOGY

Building a comprehensive road spatial data framework in Jazan City, Saudi Arabia, requires a series of systematic steps that utilize GIS and open-source data. This framework is essential for effective road design and maintenance activities. To meet these requirements, this study employed a different methodology. The main steps of the process are highlighted in **Figure 2.**

- Identify Goals and Stakeholders;
- Establish the Comprehensive Spatial Data Framework (CSDF) for the Jazan City road network;
- Focus on improving road design efficiency;
- Select the methods and techniques applied, including the study area, codes, and design and maintenance software;
- Gather data for road design and maintenance, including coordinates of the road centerline, cross-section using Topcon total station, soil data samples, traffic data, and attribute data for modeling the road network database;
- Execute the structural and geometric design using manual calculations and AutoCAD Civil 3D;
- Complete the analysis for road design and model the Jazan roads geodatabase;
- Link GIS data with engineering design software (e.g., AutoCAD, Civil 3D) to streamline the design process;
- Create the asphalt road earthwork cost estimate.

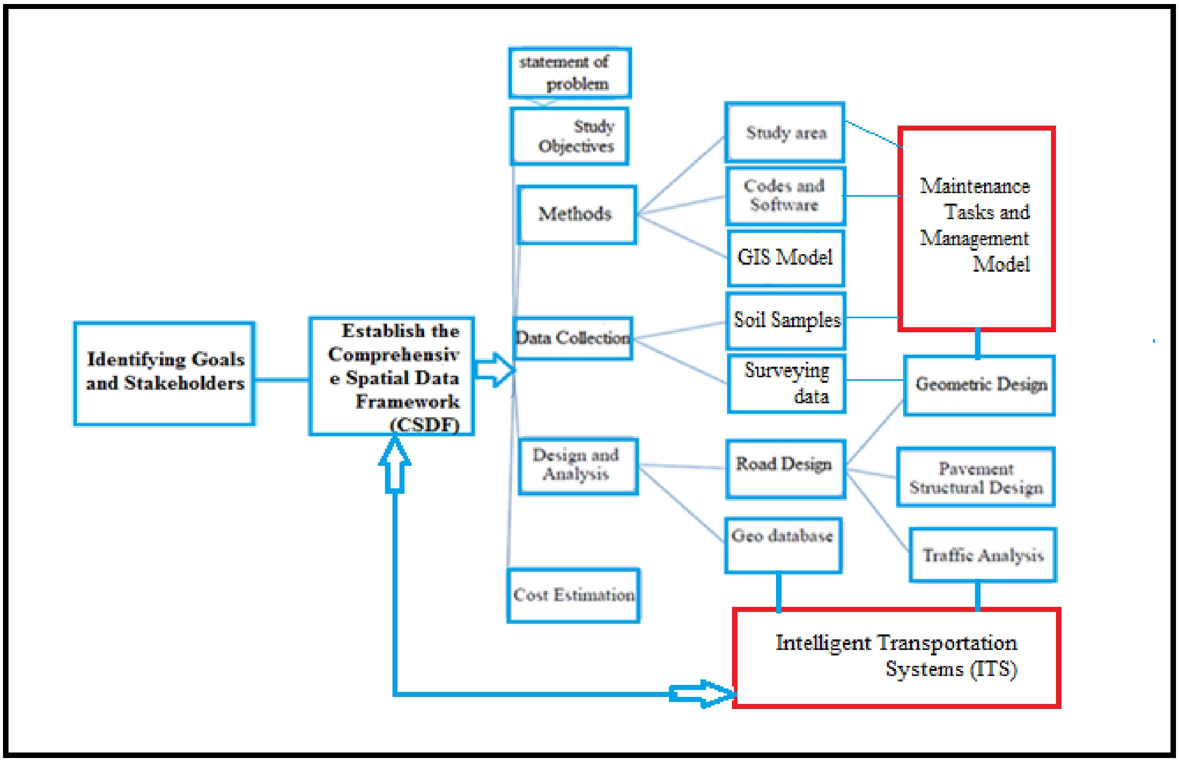

FIGURE2.Flow chart of methodology.

C. *DATA COLLECTION AND METHODS OF PROCESSING AND CALCULATIONS*

This section outlines the location data collected for the project, which was conducted on King Abdullah University Road and Alshawajrah Road, connected by this road. The information consists of several sections:

- Gathering detailed surveying data from the road site using Total Station Topcon version 7500;
- Collecting traffic data;
- Capturing Jazan roads; and
- Gathering soil samples.

1) Collecting Detailed Surveying Data

The 3D coordinates from surveys conducted in the field or study area of the road were collected from a baseline with known coordinates using Total Station Topcon 7500 (Table **1** shows the specifications). Moreover, survey data was collected systematically for 7. the road's geometric design, providing elevation, easting, and northing coordinates of the observed sites. These details were subsequently imported into AutoCAD Civil 3D[20].

TABLE 1
SPECIFICATIONS OF THE TOPCON GT-7500 TOTAL STATION

Items	Distance measuring Accuracy	Angle measurement accuracy	Slope distance measuring accuracy	Measuring range
accuracy	± (2 mm + 2 ppm of distance)	Horizontal Angle: ± 2" (seconds) Vertical Angle: ± 2" (seconds)	Typically ± (2 mm + 2 ppm)	With prism up to 5,000 m

In the study area (the road), 269 locations with coordinates (Easting, Northing, and Elevation) were observed using the Topcon total station from base line. The accuracy of horizontal and vertical coordinates, after checking the backsight, equals (delta E = -0.003 m, delta N =-0.002 m, and delta elevation = +0.001 m). The local datum of the collected coordinates is (Ain_el_Abd_UTM_Zone_38N). **Table 2** and **Figure 3** show the statistical summary of the detailed surveying data include the minimum, maximum, mean, and standard deviation of Easting, Northing, and height, respectively.

TABLE 2
STATISTICS OF THE ROAD SURVEY DATA COLLECTION

Statistic Expression	Easting (in meters)	Northing (in meters)	Elevations (in meters)
Minimum	**242128.268**	**1879575.569**	**7.795**
Maximum	**242407.040**	**1880501.975**	**11.132**
Mean:	**242214.788**	**1880030.400**	**9.799**
Standard Deviation:	**59.295**	**299.777**	**0.844**

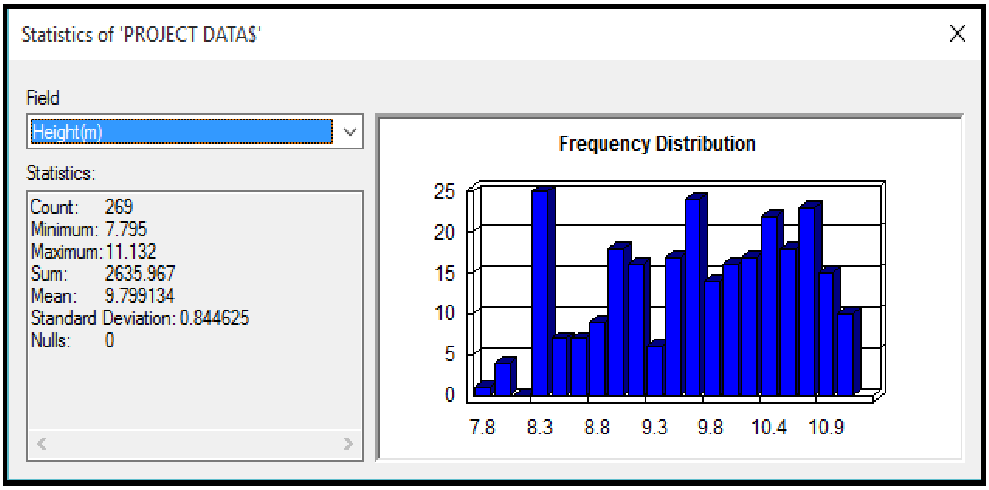

FIGURE 3. Statistics of the road's height data.

2) TRAFFIC DATA

Traffic data collection is a valuable tool that provides essential information for managing traffic and improving infrastructure. When processed in real-time, traffic data can enhance traffic flow, identify existing congestion points, and regulate urban density [21, 22]. There are various methods for gathering traffic data, including manual vehicle counts, passive and active infrared, passive magnetic, microwave radar, both passive and ultrasonic acoustics, and video image detection. In this investigation, the manual approach was employed.

3) DESCRIPTIVE DATA OF JAZAN ROADS

Before selecting a data collection approach, it is crucial to 6. determine the type of data required for the project [23]. The study area comprises 10,660 local roads, including the main thoroughfares that connect the Jazan region in four directions and pass through the neighborhoods of Jazan City. These roads also link the scheme roads both inside and outside the main thoroughfares. The most important components of the road description include the road number, length, width, direction, number of lanes, current condition of the road, and other relevant descriptive road data.

4) GATHERING SOIL SAMPLES

Soil samples were collected from the road site for this investigation and organized according to laboratory test specifications [24, 25]. Three soil samples were taken from the study road and distributed along its length. All samples were mixed in the lab before conducting tests. The following laboratory tests were performed on the road soil:

a. Particle Size Distribution (Sieve Analysis);
b. The Standard Proctor Test for compaction; and
c. California Bearing Ratio (CBR).

a. Sieve Analysis

Sieve analysis is used to weigh and allow granular materials to pass through a series of sieves with progressively smaller mesh sizes in geology, chemical engineering, and civil engineering to ascertain the material's particle size distribution or gradation. For soil particles larger than 75 microns, both dry and wet sieve examinations are conducted to quantitatively analyze the particle/grain size distribution. If the soil particles have a silt or clay coating, wet sieve analysis is also necessary. For soil particles larger than 4.75 mm and less than 75 microns, dry sieve analysis is used [26]. The following formulas are used to determine the percentages of passing and retained:

$$\mathrm{IPR} = \frac{\mathrm{IMR}}{\mathrm{M}} * 100 \qquad (1)$$

$$\mathrm{PP} = \mathrm{PCP} - \mathrm{IPR} \qquad (2)$$

$$\mathrm{PP} = 100 - \mathrm{CPR} \qquad (3)$$

$$\mathrm{RPP} = \mathrm{PP} + \mathrm{Aggregatecorrectionfactor} \ (4)$$

Where:

IPR: Individual Percent Retained, CPR: Cumulative Percent Retained, M: Total Dry Sample mass before washing, IMR: Individual Mass Retained, CMR: Cumulative Mass Retained, PP: Calculated Percent Passing, PCP: Previously Calculated Percent Passing, and RPP: Reported Percent Passing.

b. The Standard Proctor test

The Proctor compaction test involves compacting soil samples at a predetermined water content using a standard compaction energy in a traditional mold. Compaction tests, also known as soil compaction tests, are used to determine the density and moisture content of soil, which is critical for building projects and roadways [27–29]. The following formulas are used to calculate the compaction test:

$$\gamma = \frac{w_2 - w_1}{Volumeofmold} (5)$$

$$\gamma_{dry} = \frac{\gamma}{1 + \frac{w\%}{100}} (6)$$

$$w\% = \frac{weightofmoist}{dryweightofsoil} * 100 = \frac{w(can+wetsoil) - w(can+drysoil)}{w(can+drysoil) - w(can)} \qquad (7)$$

$$\gamma zeroairvoid = \frac{\gamma water}{\frac{w\%}{100} + \frac{1}{Gs}} (8)$$

$$\text{Pavement Layer of mold} = \frac{\pi D^2}{4} * H = \frac{\pi 9.98^2}{4} * 12.75 = 997.381 \ cm (9)$$

Where:

γ: $moist\ unit\ weight$, γ_{dry}: $dry\ unit\ weight$, w_1= weight of mold+ base plate, w_1: weight of mold + base plate + compacted moist soil in the mold, and $w\%$ moisture content(M.C).

c. California Bearing Ratio (CBR)

The California Bearing Ratio (CBR) is the percentage difference between the force required to move a standard circular piston through a mass of soil at a rate of 1.25 mm/min to a specific depth and the force required to achieve the same with a standard material. The CBR test is used to evaluate the mechanical strength and load-bearing capacity of highway sub-bases and sub-grades.CBR testing is rarely conducted as part of routine site investigations. The conversion of penetration findings to CBR values is made possible by calibration charts. Subsequently, we estimate the sub-grade surface modulus using the equation derived from CBR [30-32].

The calculation methods for CBR include the following equations:

$$\rho = \frac{m_3 - m_2}{V_m} (10)$$

$\rho_d = \left(\frac{100}{100+w}\right)\rho$ (11)

$\rho_{ds} = \left(\frac{\rho_d}{1+\frac{Ax}{1000V_m}}\right)$ (12)

Where:

m_3: The mass of soil, mold, and base plate (in g.), m_2: The mass of mold and base plate (in g.), V_m: The volume of mould (in cm^3), ρ_d: initial dry density(in kg/m^3), ρ_{ds} : The dry density (in Mg/m^3), w: the moisture content of soil (in %), A: the area of cross-section of the mold (in mm^2), x: the increase in sample height after swelling (in mm).

5. Geometric Design Using AutoCAD Civil 3D

A road that is designed and developed in accordance with regulations is deemed safe [33–36]. The following design criteria were applied to the profile, cross-section, and horizontal centerline geometry of the study road in Jazan, in accordance with AASHTO specifications, ensuring safety measures at a reasonable cost. The following criteria were used in the design of the study road:

a. The maximum super elevation rate is 4%;
b. The design speed is 100 km/h;
c. Radius of Curve: 490 m
d. Deflection angles: 3.5 degree;
e. The coefficient of friction is 0.15;
f. The minimum K for sag curves is 33 m;
g. The road's width is 20 meters;
h. For crest curves, the minimum K is 17 m; and
i. No shoulder(urban road) [37-41]. **Table 3** shows the values of the design parameters for simple curve.

The design steps in AutoCAD Civil 3D include the following:

a. Import a text format point file (Easting, Northing, and elevation) of the proposed road in Jazan City into the AutoCAD Civil 3D environment;
b. Use the alignment creation tool to create alignment (Figure 3);
c. Determine the super elevation based on the provided alignment;
d. Establish a surface and contour map for road drainage
e. system purposes (see **Figure 4**);
f. Design the existing profile of the surface and create a grade line and vertical curves (crest and sag) as highlighted in **Figure 5**;
g. Determine the thicknesses of the road layers according the requirement of design(see **Figure 6);**
h. Construct the assembly (a typical cross-section) as shown in Figure 7;
i. Construct a 3D model depiction of a corridor using a mix of horizontal, vertical, and cross-sectional features. Corridors are used to find data for construction projects, analyze sight distances, and compute the amount of earthwork needed;
j. Create a report with a volume table;
k. Create three road iterations, compare them, and select the alignment that minimizes fill volumes by adjusting the vertical alignment (crest) parameters. The calculations of crest vertical curve design parameters used in three iterations are displayed in Table 4, and Table 5 shows the vertical design parameters used in three iterations of the sag curve.

TABLE 3

VALUES OF THE SIMPLE CIRCULAR CURVE'S DESIGN PARAMETERS

Name of Curve Item	Calculated Value
Tangent (T)	46.46 m
Long Chord (L)	92.612 m
External Distance (E)	2.39 m
Middle Ordinate Distance (M)	2.37 m
Length of Circular Curve (L.C.C)	92.619 m
Degree of Curve (D)	3.88 degrees

TABLE 4
CREST VERTICAL CURVE DESIGN PARAMETERS USED IN THREE ITERATIONS

Name of Vertical Curve Item curve	Initial Grade (g_1%)	Final Grade (g_2%)	Road Elements and Formula	Design Value	Note
FCC – Algebraic difference between the two tangent grades A%(A%)	+1	-3.5	(A%) = (g2%) - (g1%) (13)	-4.5%	It.1
FCC- SSD			$SSD = \frac{v*t}{3.6} + \frac{v^2}{254*(f \pm g)}$(m)(14)	190.233 m	It.1
L FCC (16)			$\frac{A*SSD^2}{200(\sqrt{h1}+\sqrt{h2})^2}$ (15)	247.490 m	It.1_SSD <L FCC (Okay, is used for design)
L FCC			$2*SSD - \frac{200(\sqrt{h1}+\sqrt{h2})^2}{A}$ (m) (16)	234.254 m	It.1_SSD > L FCC (Not Okay)
SCC – Grade Angle (A%)	+1	-2.5	(A%)	-3.5%- 3.5%	It.2
SCC - SSD (m)SCC - SSD (m)SCC - SSD (m)			SSD(m)	184.831 m	It.2
L SCC (m)			$\frac{A*SSD^2}{200(\sqrt{h1}+\sqrt{h2})^2}$	181.715 m	It.2_SSD <L SCC (Not Okay)
L SCC			$2*SSD - \frac{200(\sqrt{h1}+\sqrt{h2})^2}{A}$(m)	181.663 m	It.2_SSD > L SCC (Okay, is used for design)
THCC – Grade Angle (A%)	+2	-1	(A%)	-2.5%- 2.5%	It.3
SCC- SSD			SSD(m)	182.274 m	It.3
L THCC (m)			$\frac{A*SSD^2}{200(\sqrt{h1}+\sqrt{h2})^2}$(m)	151.478 m	It.2_SSD <L THCC (Not Okay)
L THCC			$2*SSD - \frac{200(\sqrt{h1}+\sqrt{h2})^2}{A}$ (m)	145.216 m	It.2_SSD > L THCC (Okay, used for design)

TABLE 5
SAG VERTICAL CURVE DESIGN PARAMETERS USED IN THREE ITERATIONS (SCENARIOS)

Name of Vertical Curve Item	Initial Grade (g_1%)	Final Grade (g_2%)	Road Elements and Formula (m)	Design Value	Note
FCC – Algebraic difference between the two tangent grades(A %)	-3.5	+1	A%	+4.5%	It.1
FSC - SSD (m)			$SSD = \frac{v*t}{3.6} + \frac{v^2}{254*(f \pm g)}$(m)	190.233 m	It.1
L_{FSC} (m) (17)			$\frac{A*SSD\hat{}2}{200(h1+SSD*tan\beta)}$(m) (17)	207.687 m	It.1_SSD <L_{FSC} (Okay, is used for design)
L_{FSC}			2*SSD -$\frac{200(h1+SSD.tan.\beta)}{A}$(m) (18)	338.828 m	It.1_SSD > L_{FSC} (Not Okay)
SSC – Grade Angle (A%)	-2.5	+1	A%	-3.5 %	It.2
SSC - SSD (m)			SSD(m)	184.831 m	It.2
L_{SSC} (m)			$\frac{A*SSD^2}{200(\sqrt{h1}+\sqrt{h2})^2}$(m)	156.248 m	It.2_SSD< L_{SCC} (Not Okay)
L_{SSC}			$2*SSD - \frac{200(\sqrt{h1}+\sqrt{h2})^2}{A}$(m)	151.020 m	It.2_SSD> L_{SCC} (Okay, is used for design)
THSC – Grade Angle (A%)	-1	+2	A%	-2.5 %	It.3
SCC-SSD			SSD(m)	182.274 m	It.3
L_{THSC} (m)			$\frac{A*SSD^2}{200(\sqrt{h1}+\sqrt{h2})^2}$	131.788 m	It.2_SSD< L_{THCC} (Not Okay)
L_{THSC}			$2*SSD - \frac{200(\sqrt{h1}+\sqrt{h2})^2}{A}$(m)	112.441 m	It.2_SSD> L_{THCC} (Okay, is used for design)

Where:

Crest vertical curve

(FCC): First Crest Curve, (SSD): Stopping Sight Distance: , (A%), : Grade angle, (L FCC): Length of the First Crest Curve, (It.1): Iteration 1, (SCC): Second Crest Curve, (It.2): Iteration 2, (THCC): Third Crest Curve, (h1): driver eye height = 1.08 m, (h2): objective height = 0.60 m, (t): perception reaction time (1.5 seconds), (f): side friction = 0.3 m.

Sag vertical curve

(FSC): First Sag Curve, (SSD): Stopping Sight Distance: , (A%), : Grade angle, (L FSC): Length of the First Sag Curve, (It.1): Iteration 1, (SSC): Second Sag Curve, (It.2): Iteration 2, (THSC): Third Sag Curve, (h1): driver eye height = 1.08 m, (h2): objective height = 0.60 m, (β): 1 degree, (t): perception reaction time (1.5 seconds), side friction= 0.3 m.

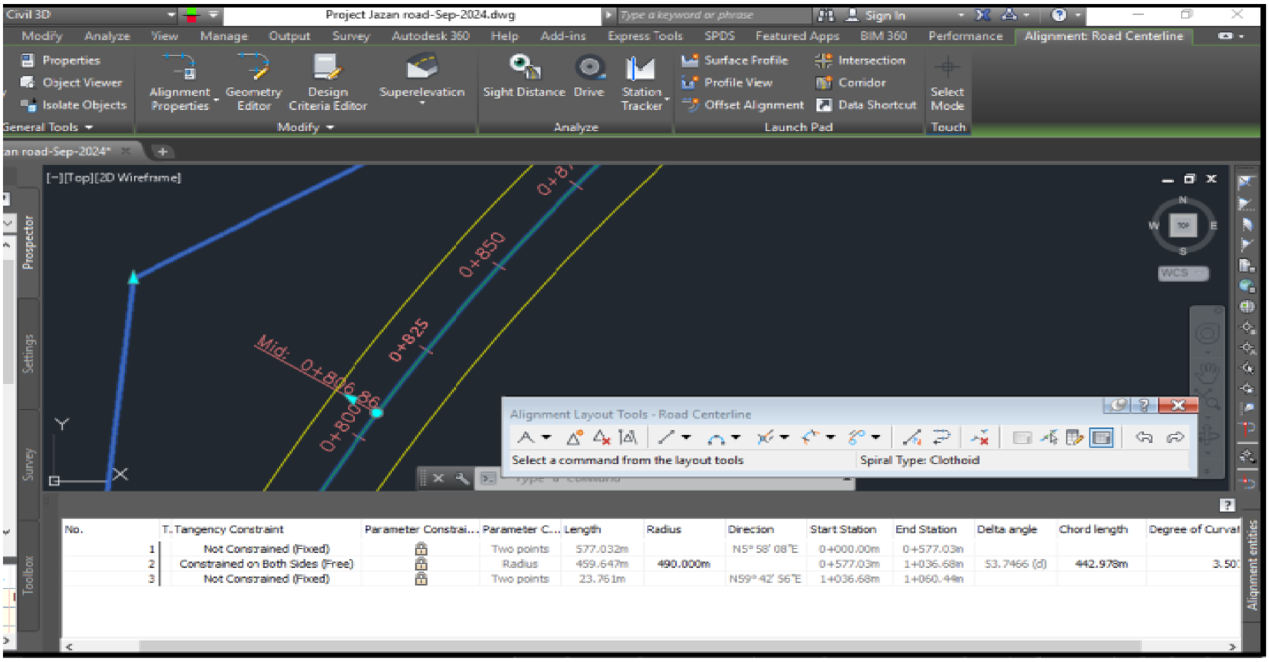

FIGURE 3.The alignment of the study road in AutoCAD Civil 3D.

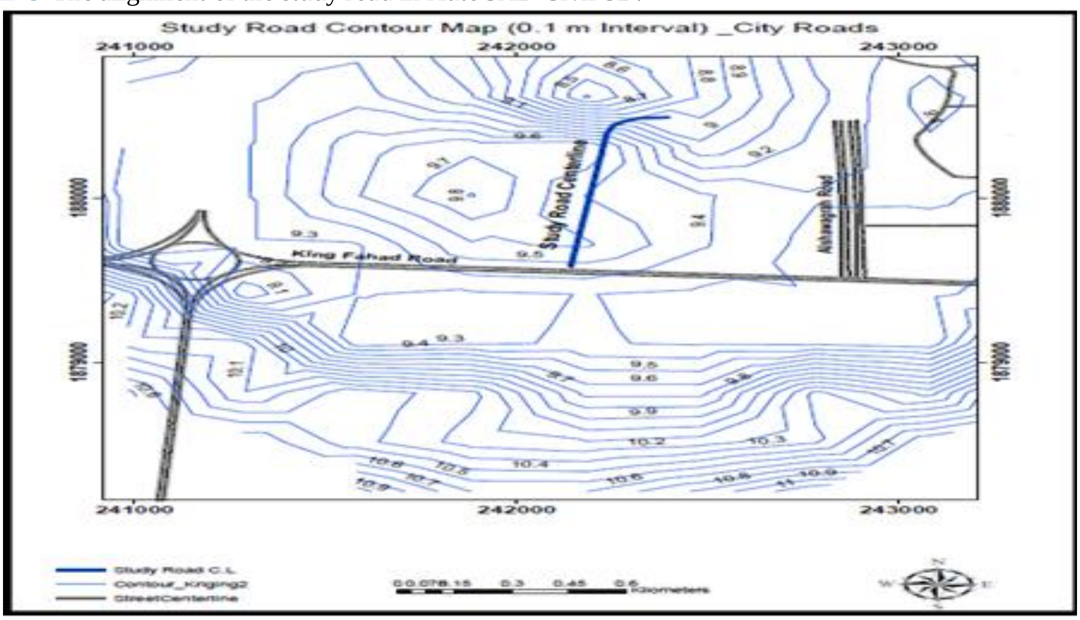

FIGURE4.Contour map of the study road's contour map (was created using ArcGIS 10.4).

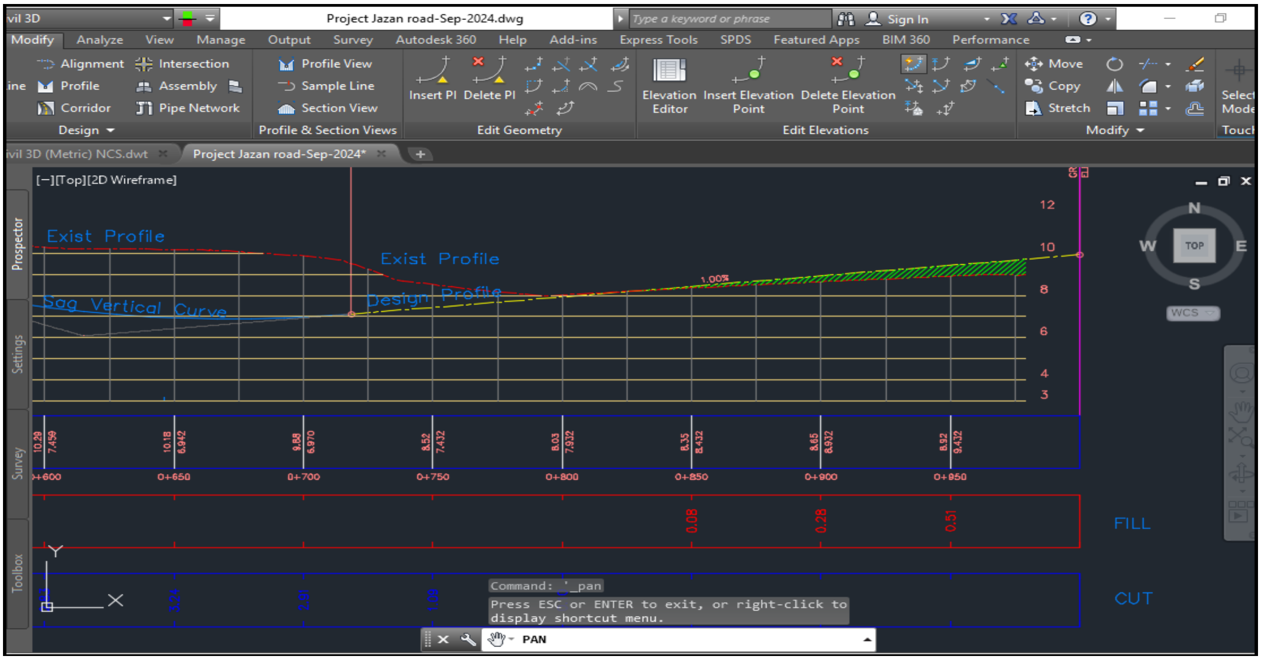

FIGURE5.Profile of natural ground level and design profile (from AutoCAD Civil 3D).

6. Flexible Pavement Design

The primary function of highway pavement, composed of layers of processed materials placed over a naturally existing soil sub-grade, is to distribute applied vehicle loads to the sub-grade. Flexible pavements and rigid pavements are the two types of pavement generally accepted for this purpose. This section provides an overview of pavement types, layers, and their functions, as well as pavement failures. Errors in pavement design can lead to premature failure. The designer has complete control over the paving materials and layer thickness [42–46].

a) Road Layer Thickness Calculation

The equations used for calculating road layer thickness are:

$$SN1 = a_1 D_1 \text{ inch} \quad (19)$$

$$SN2 = a_1 D_1 + a_2 D_2 m_2 \quad (20)$$

$$SN3 = a_1 D_1 + a_2 D_2 m_2 + a_3 D_3 m_3 \quad (21)$$

Where:

SN1: Asphalt Course, SN2: Base Course, SN3: Sub-Base Course, D1: layer thickness (in.), a_i: i[th] Structural layer coefficient, SN: structural Number.

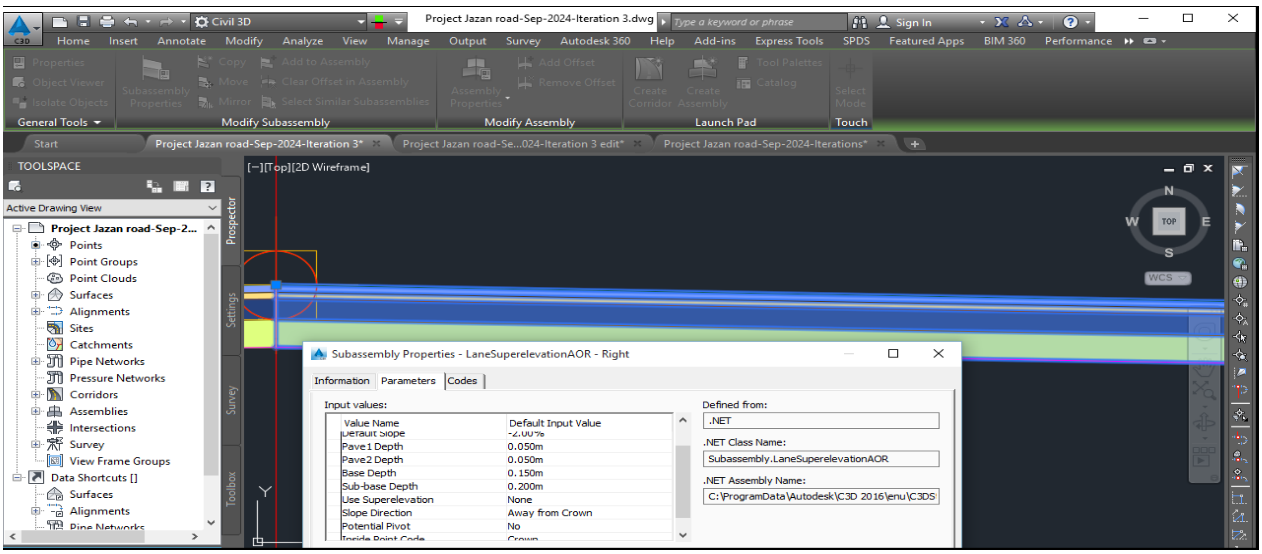

FIGURE 6.Construction assembly and design parameters inputted (derived from AutoCAD Civil 3D).

b) Calculation the traffic analysis

This study's primary traffic analysis focuses on lane computation and autonomous lane monitoring systems that maintain drivers' lanes. Roadways are divided into several cells by cell models, such as lane-changing and car-following models, with every vehicle positioned in one of these cells. The following equations are employed in this context:

Future ADT = ADT (1+Growth Rate)^n (22)

DDHV = ADT (or ADT) * K * D (23)

No. of Lane = DDHV/Capacity (24)

Where:

ADT: Average Daily Traffic, DDHV: Directional Design-Hour Volume, K: Peak-hour traffic, D: Peak direction generally carries.

c) Equivalent Single Axle Load (ESAL)

The conversion is frequently used to standardize a single axle load equivalent to 18,000 lb (80 kN). The AASHTO Guide to Pavement Structure (1993) states that the equivalent surface area loss (ESAL) is the ratio of the damage caused by an axle passing over pavement to the damage caused by a standard axle, typically an 80 kN single axle load passing over the same pavement. Equation 25 presents this [47,48]. The damage factor caused by Equivalent Single Axle Load (ESAL) is calculated using equation 25.

$$DF = k\left(\frac{Qi}{Qs}\right)^4 \quad (25)$$

Where:

DF: Damage Factor, Qi: Actual Load, Qs: Standard Single Axle Load 80 kN, k: 1 for single, 0.086 for tandem, and 0.053 for triaxial load.

Equivalent Single Axle Load (ESAL) is derived using equations (26) and (27).

orESAL = W_{80KN} *DD* LD *TF*365*G

ADT*TKS *DD* LD *TF*365*G(26)

$$G = \frac{(1+g)^n}{g} \quad (27)$$

Where:

W_{80KN}: Total ESAL of vehicles (ESAL) ADT: Average daily traffic, TKS: Percentage of truck traffic, DD: Directional distribution of truck traffic, LD: Lane distribution of truck traffic, TF: Average truck factor; g: Annual traffic growth factor equal 4%,

W80 KN :Total ESAL of traffic.

7. Road Cost Estimation

Since all layers will be constructed on the same formation level, the earthwork cost is calculated prior to design and is considered a constant for all three design approaches. The construction cost of each layer for each design method will depend on the projected thickness.

8. Design and Structure of Jazan Roads Geo-database Using GIS

As previously stated, the database has a direct impact on and is a major factor in a GIS's cost. A database serves as the foundation for a GIS, enabling users to develop applications, perform programming, evaluate and extract secondary data, assist with road maintenance procedures, and ultimately support decision-making [49,50]. The basis for the data placed in the database is determined by the database design. Depending on the type of data, the inventory data in this design is divided into three groups. The data in this design is derived directly from the field telemetry tool and includes tabular, spatial, and other types of data. **Table 6**and **Figure 7** show the geodatabase of the Jazan City roads network (uploaded from ArcGIS 10.4).Designing a database for roads and Intelligent Transportation Systems (ITS) using ArcGIS 10.4 requires a comprehensive approach. Here's a unique step-by-step guide to effectively structure and implement the database:

a. Establish project goals (traffic patterns, incident reports);
b. Collect stakeholder input, including urban planners, transportation officials, and emergency services, to gather insights on their data needs;
c. Plan the database framework and define tables for additional data, such as traffic statistics and maintenance logs (e.g., linking traffic volumes to specific road segments);
d. Incorporate spatial data and collect open-source spatial data through surveys, remote sensing, or existing GIS datasets. Furthermore, import the spatial datasets into the geodatabase using ArcGIS 10.4;
e. Document metadata, ensuring comprehensive metadata management tools for consistency;
f. Test database performance and Solicit user feedback during testing to identify areas for improvement; and
g. Make the database available to users and stakeholders, ensuring they are informed about its features.

TABLE 6

SAMPLE OF MANUAL INPUT OF DESCRIPTIVE DATA OF JAZAN CITY ROAD NETWORK

Object	Status	Street Name	width	No. of Lanes	Shape Length (m)
5999	Exist	Tarig bin Ziyad	13	3	267.436
6000	Exist	Tarig bin Ziyad	13	3	71.009
6001	Exist	Tarig bin Ziyad	11	2	47.385
6002	Exist	Prince Abdulaziz bin Nasser	13	2	245.107
6003	Exist	Prince Abdulaziz bin Nasser	13	2	244.137
6004	Exist	Prince Abdulaziz bin Nasser	13	2	184.578
6005	Exist	Prince Abdulaziz bin Nasser	13	2	174.411
6006	Exist	Prince Abdulaziz bin Nasser	13	2	520.963
6007	Exist	Prince Abdulaziz bin Nasser	13	2	132.817
6008	Exist	Prince Abdulaziz bin Nasser	11.5	2	172.69
6009	Exist	Prince Abdulaziz bin Nasser	11.5	2	263.193
6010	Exist	Prince Abdulaziz bin Nasser	13	2	236.746
6011	Exist	Prince Abdulaziz bin Nasser	13	2	715.910

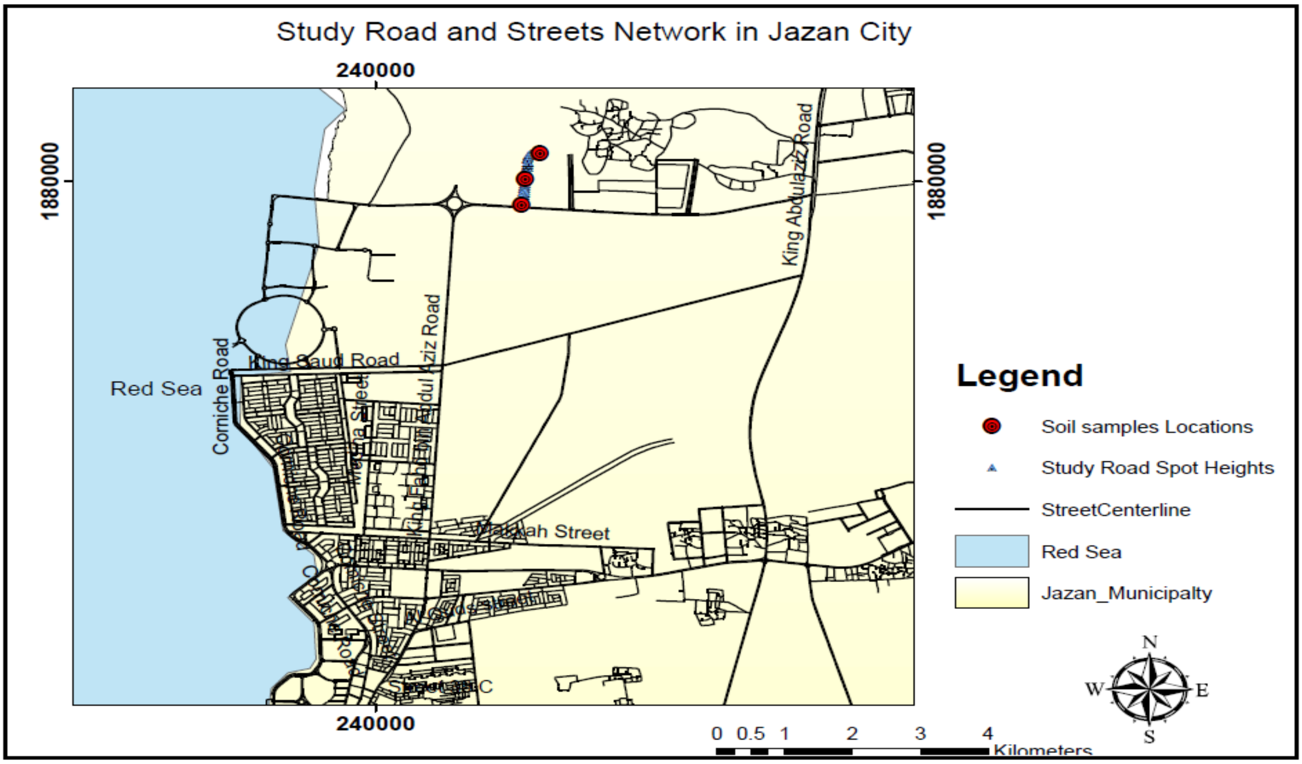

FIGURE 7. Jazan City Street network (derived from ArcGIS 10.4)

III. RESULTS

The findings of this study relate to the calculation parameters and road design in AutoCAD Civil 3D. These results include the following:

A. OPTIMUM ROUTE SELECTION FOR CONSTRUCTION

Using AutoCAD Civil 3D, the final result, as shown in **Table 7** and **Figure 8,** indicates that the third recommended road is the optimal path, with a success percentage of 1.044%. The same outcomes were achieved when applying the mini-max method to optimize the volumes according to the three iterations of design parameters calculated in **Tables4** and **5**.

TABLE 7.
THE RESULTS OF THREE SUGGESTED ROUTES OF THE STUDY ROAD

Iteration	Cumulative Cut Volume (m^3)(m^3)(m^3)(m^3)(m^3)	Cumulative Fill Volume (m^3)	Percentage of Cut Volume (%)	Percentage of Fill Volume (%)
1	**21539.32**	**422469.04**	**26.06**	**96.02**
2	**26348.78**	**12926.44**	**31.88**	**2.93%**
3	**34772.18**	**4595.200**	**42.06**	**1.044%**
Total Sum.	**82660.28**	**439990.7**	**100%**	**100%**

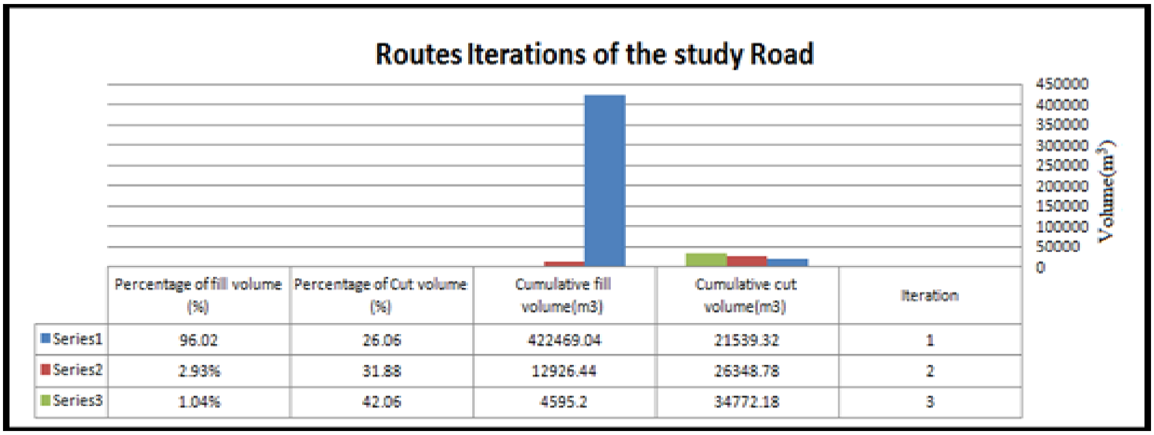

FIGURE 8. Iterations of route design using AutoCAD Civil 3D.

B. RESULTS OF SOIL TESTS

1) SIEVE ANALYSIS TEST

Equations (1-4) are used to calculate the values the percent of passing and retained. **Table 8 and Figure 9** show the results of the sieve analysis.

2) COMPACTION TEST

The compaction test demonstrated relationship between the dry density and moisture content, presenting a maximum dry density of 2.303 gm/cm³ at a moisture content of 5.1%. Equations (5-9) are used to calculate the parameters of the compaction test**. Figure 10**illustrates the results of the compaction test.

TABLE 8.
SIEVE ANALYSIS TEST

Sieve Size (mm)	**50**	**25**	**11.2**	**4**	**2**	**0.6**	**0.25**	**0.15**	**0.063**	**Pan**
Percent Finer (%)	**100**	**69.3**	**52.8**	**46.2**	**40.1**	**32.1**	**29.7**	**16.7**	**3.97**	**0**

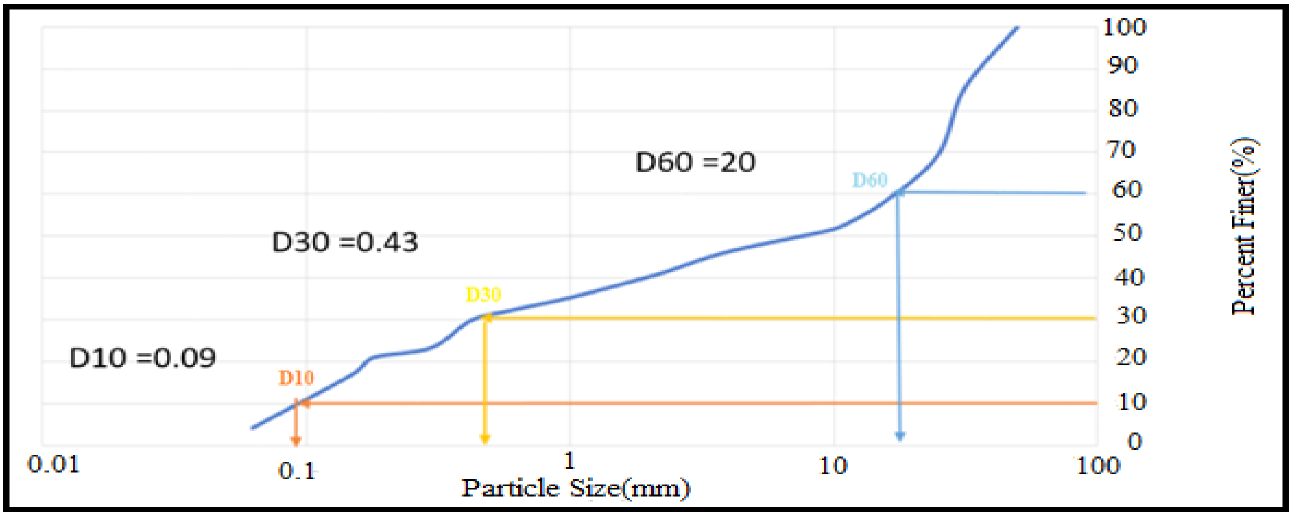

FIGURE 9. Graph of sieve analysis test of the soil sample from the road.

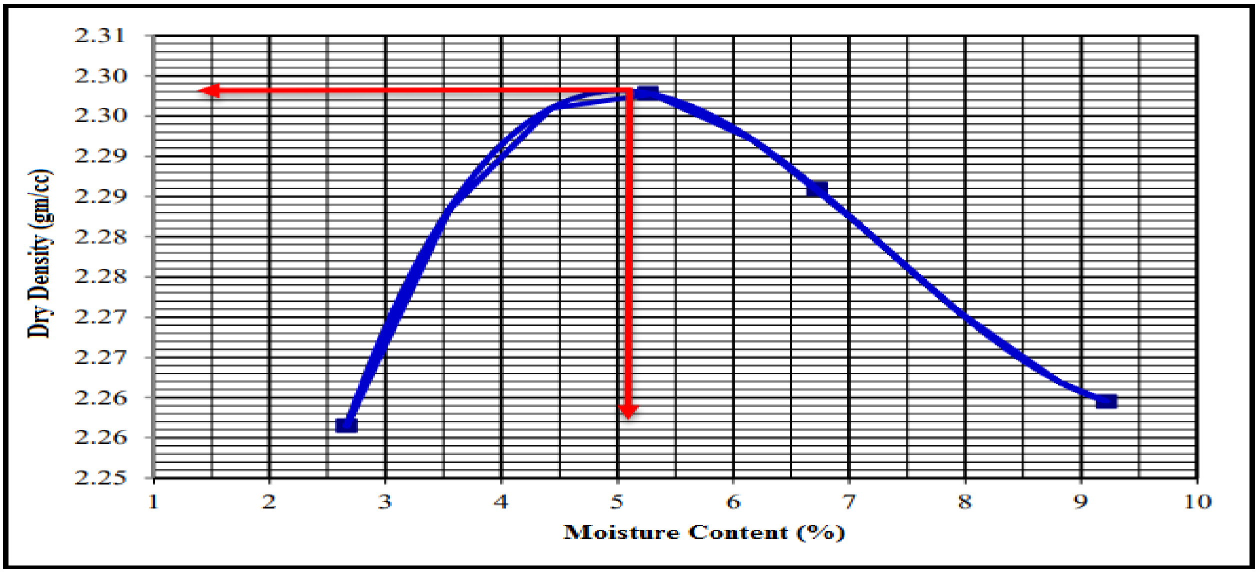

FIGURE 10. Compaction curve of dry density(gm/cc)vs. Moisture content(%)

3) CALIFORNIA BEARING RATIO (CBR)

Using equations (10-12) to determine the parameters of the California Bearing Ratio (CBR).**Table 9 and Figure 11**show the graph of CBR of the road soil sample to determine the optimum moisture content.

TABLE 9.
CBR TEST RESULTS OF THE UN SOAKED EMBANKMENT

Compaction Effort	CBR (%)	
(blows)	2.54 mm	5.08
10	19.9	27.3
30	47.3	50.5
65	97.7	100.9

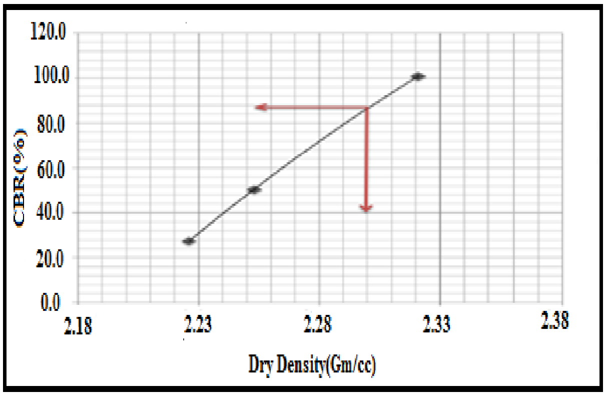

FIGURE 11. The dry density vs. the soaked CBR (%)

C. FLEXIBLE PAVEMENT DESIGN

This paper presents the main flexible pavement designs carried out, including the following**:**

1) Thickness of the Road Layers

Using equations (19-21), the thickness of the road layers was calculated according to the AASHTO pavement design of 1993 and presented in **Table 10. These values** are also used in AutoCAD Civil 3D as parameters in road design, as shown in **Figure 6**.

TABLE 10.
ROAD - AASHTO PAVEMENT DESIGN (1993) AND CALCULATED THICKNESS OF ROAD LAYERS

Data			Serial No.	Design Items				
Asphalt Layer E = 350,000 (psi)			SN	Structural Coefficient	Drainage Coefficient	Calculated Thickness (in)	Required Thickness (cm)	Design Value (cm)
			1.9	0.39	1	4.87	12.4	10
	CBR %	E (psi) from chart						
Granular Base	87	28000	2.2	0.135	1.2	1.54 use 6	15.25	15
Granular Sub Base	87	19000	3.5	0.134		7.56	19.2	20
Sub-grade	4	5000	-	-	-		-	-

2) Traffic analysis

Table 11 shows the parameter data used for calculating the number of lanes in the study road in Jazan. Using formulas (22-24), the results are presented in **Table 12.** Two lanes were calculated for the study road; **Figure 13**illustrates the lanes and vehicle locations of vehicle passing.

TABLE 11.
PARAMETERS DESIGN NO. OF LANE

Design Parameter Name	The Value
Design Period	20 years
Growth rate	4%
Design Capacity of lane (pc/lane)	1300
Peak-Hour Traffic (K)	0.1
Peak Direction Generally Carries (D)	1
ADT (vehicle/day)	6468
Future ADT (pc/lane)	14172

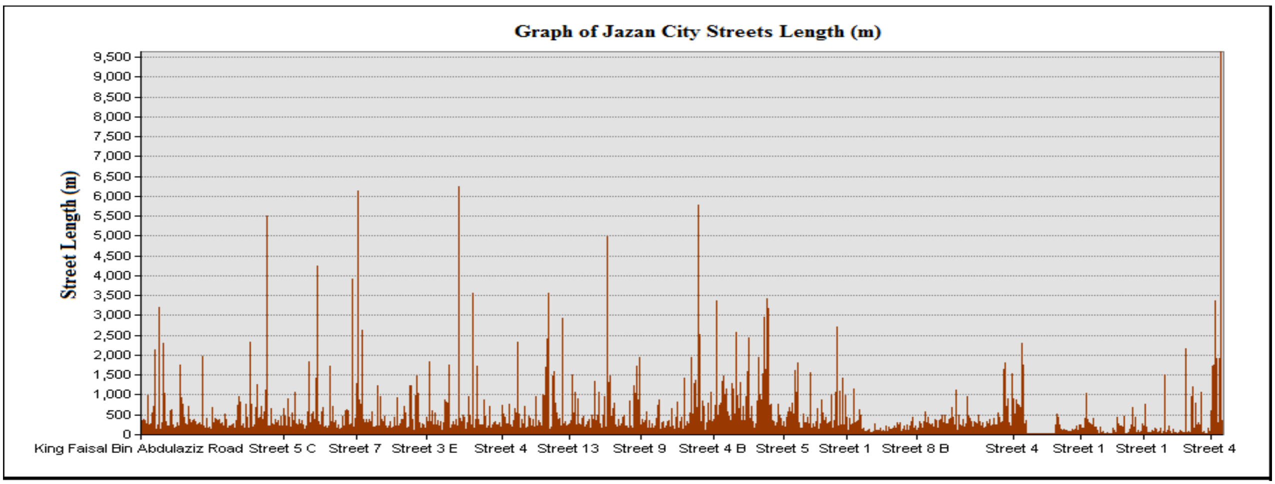

FIGURE 12.Jazan City streets graph according to length in meters

TABLE 12.
CALCULATION OF NUMBER OF LANES

Parameters	Results
ADT	$\boldsymbol{ADT} = \mathbf{6468}\ (1+0.04)^{20} = 14172$ pc/lane
DDHV	DDHV = 14172 * 0.1 * 1 =1417veh/hr
Number of Lanes	No. of lanes = 1417/1300 = 1.09 ≈ 2 lanes/direction.

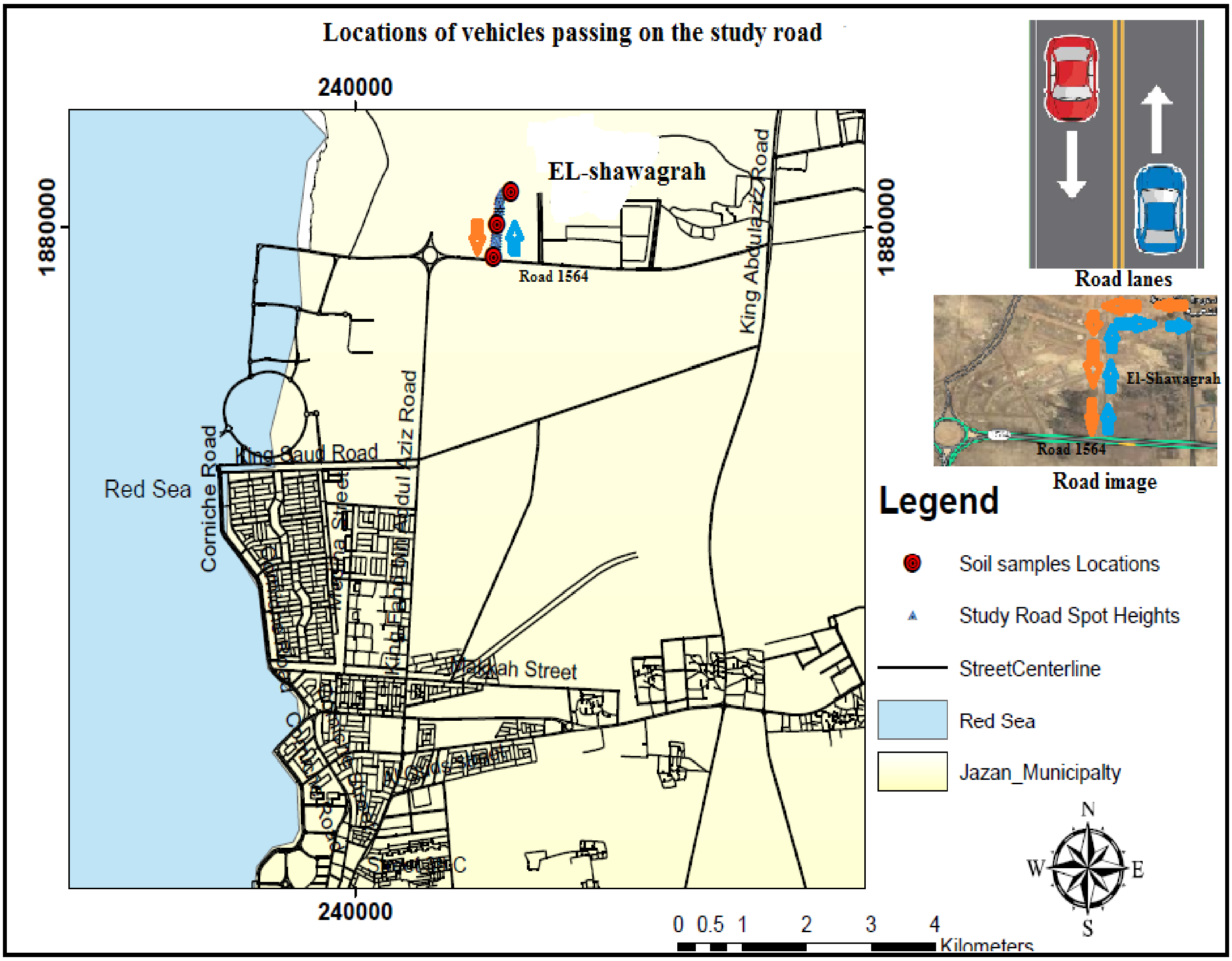

FIGURE 13.Map of lanes and locations of vehicles passing on the road (derived from ArcGIS 10.4)

3) Equivalent Single Axle Load (ESAL)

Using equations (36-38), the traffic count was made for a two-way, two-lane highway section, with a directional distribution (DD) equal to 0.80 (80%), lane distribution (LD) equal to 0.70 (70%), and traffic factor (TF) equal to 20.2. The value of ESAL for 20 years equals 9523411.627, assuming ESAL of each axle is equal to 850.53.

$$G = \frac{(1+0.04)^{20}}{0.04} = 54.78$$

The Total ESAL = 850.53 * 0.80 *0.70*365*54.78=9523411.627

D. ANALYSIS OF GEODATABASE IN JAZAN ROAD NETWOR USING ARCGIS 10.4

This study utilized GIS tools to establish a geodatabase for the Jazan roads network to analyze traffic trends, identify congested locations, and assess road usage patterns. Furthermore, analytical models were created based on usage data and environmental factors to evaluate the current state of roads and project future maintenance needs. The digital model of the road network in Jazan, developed using the capabilities of ArcGIS 10.4, facilitated easy queries. **Table 13** provides specific descriptive statistics about the characteristics of the Jazan City roadway. The geodatabase model of the Jazan road network is designed as a flexible model capable of editing, storing, plotting maps, and analyzing. Additionally, analysis can be conducted to choose the road network graph based on the length of the roads (see **Figure 12**).

TABLE 13.
DESCRIPTIVE STATISTICS OF THE ROADS LENGTHS AND WIDTHS DATA IN THE STUDY AREA.

Statistic Expression	Road Length (km)	Road Width (m)
Minimum	0.05	3.500
Maximum	9.643018	133.50
Mean:	0.132476	11.244
Standard Deviation:	0.280151	6.944

E. RESULT OF COST ANALYSIS

In this study, the Jazan Comprehensive Road Spatial Data Framework (CRSDF) indicates that the construction costs of a road can vary significantly based on several factors, including site conditions, geography, materials used, and specific design specifications. However, in a developed nation, constructing a single kilometer of a standard paved road typically costs between one million and three million Saudi Riyals on average [51,52].**Table 14**shows the materials of the road, and the cost estimation is applied to the optimal route.

TABLE 14.
MATERIALS VOLUME CALCULATIONS USING AUTOCAD CIVIL 3D**.**

Iteration	Cumulative Cut Volume (m^3)	Cumulative Fill Volume (m^3)	Sub-Volume(m^3) base Layer Volume (m^3)	Base Layer Volume(m^3)	Pavement Layer Volume(m^3)
1	21539.32	422469.04	5280.47	1977.38	960.11
2	26348.78	12926.44			
3	34772.18	4595.20			

Table 15 and Figure **14** show that the third iteration is selected as the optimal path for this road because this route represents the lowest fill volume. Furthermore, the total cost of materials for iteration 3 (cut, fill, sub-base, base, and asphalt) is calculated according to the volumes and prices of the cubic meter of the volume items in Saudi Riyals.
The total basic cost of materials ($T.M_{cost}$) = 34772.18 * 1.3 * 15 + 4595.20 * 1.3 * 20 + 5280.47 * 1.3 * 30 + 1977.38 * 1.3 * 30 + 960.11 * 1.25 * 55 =**913003.793** Saudi Riyals [53].

TABLE 15. THE TOTAL COST OF MATERIALS FOR ROAD DESIGN AND CONSTRUCTION (ITERATION 3)

Iteration	**Cumulative Cut Volume (m^3)**	**Cumulative Fill Volume (m^3)**	**Sub-base Layer**	**Base Layer**	**Pavement layer**
			Volume (m^3)	**Volume (m^3)**	**Volume (m^3)**
3	**34772.18**	**4595.2**	**5280.47**	**1977.38**	**960.11**
Final Cost (Saudi Riyals)	**521582.7**	**119475.2**	**205938.33**	**77117.82**	**66007.56**

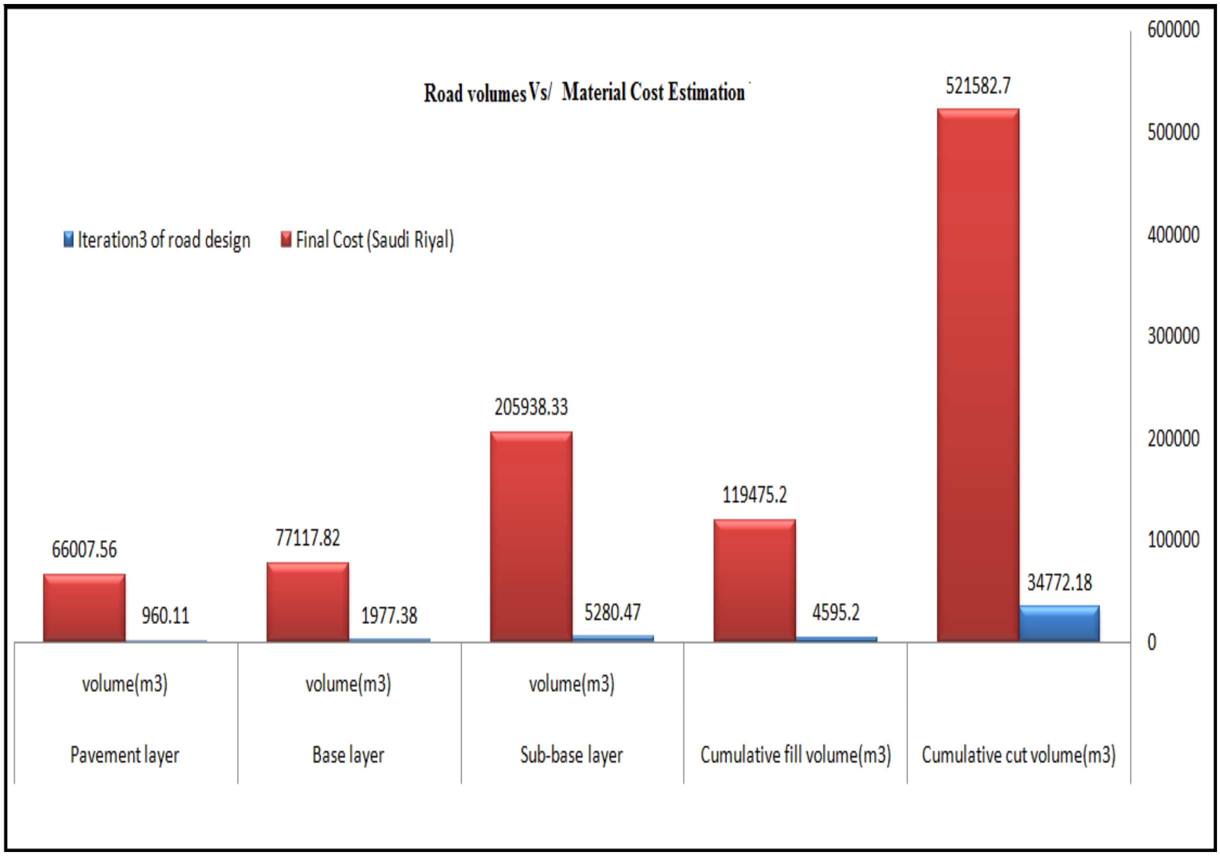

FIGURE 14. The total cost of the optimal route design per layer

This cost represents the main construction cost item for one kilometer; however, the road investigated is not one kilometer, so the projected cost for this paper is determined in **Table 16.** Material volumes include cut, fill, sub-base, base, and pavement. The price of a cubic meter, along with transportation of cut and fill with well-graded soil and asphalt, is 15, 20, 30,, 30 and 55 Saudi Riyals, respectively, according the roads contract companies in Jazan. Furthermore, the ratio of the compacted factor of well-graded soil and asphalt equals 1.3 and 1.25, respectively. For compacted layers, the computed volume increases by this ratio before determining the cost.

TABLE 16.
SUMMARY OF COST ESTIMATION OF THE STUDY ROAD

Item	Description	Actual Cost (SAR)	Costing Factor	Cost (SAR)
1	Total Materials Cost	913003.793	1.1	1,004304.17
2	Equipment Cost	186,714	1.2	224,057
3	Manpower Cost	3,650	1.1	4,015
4	Materials Testing Cost	1,330	1	1,330
	Total	1,104,697.79		,1233706.17

IV. DISCUSSIONS

This study presents a comprehensive framework for understanding the unique geographical and geological context of Jazan, established through the integration of advanced software, geographical data, and soil analysis.

The paper covers four parts and optimizes the volumes in accordance with the three design parameter iterations determined in Tables 4 and 5,which produced consistent results. Table 7 and Figure 8 demonstrate that the third suggested road is the best option.

The AASHTO classification of the Embankment Road in Jazan City is (A-1-a), with D60 = 20, D30 = 0.43, and D10 = 0.09. The soil used in this study is characterized as gravelly sand. A comparison with the Unified Classification System (USCS) indicates that the soil is coarse, retaining more than 50% (99.89 > 50) when sieved through a 0.075 mm screen. The gravelly soil can be found on road embankments and roadways, retaining over 50% (59.78 > 50) after passing through a 4.75 mm sieve.

In Figure 10 displays the results of the compaction test, illustrating the relationship between the dry density and moisture content. The highest dry density recorded was 2.303 gm/cm³ at a moisture level of 5.1%.

In **Figure 11 presents** the graph of the California Bearing Ratio (CBR) for the road soil sample, aiding in the identification of the optimal moisture level. At 100% compaction, the soaked CBR for the sub-base and base is 87%, while the sub grade equals 4%. The thickness of the road layers was estimated using equations (5–9) in accordance with the AASHTO pavement design guidelines from 1993. The results are summarized in Table 8 and are also utilized as parameters in AutoCAD Civil 3D for road design, as

This study estimates a Total Equivalent Single Axle Load (ESAL) of approximately **9,523,411.63, representing** the cumulative effect of traffic loads on the pavement over the specified duration. The significance of the Calculation

- **Road Design**: These calculations provide engineers with essential data for designing pavements capable of withstanding projected traffic loads.
- **Maintenance Planning**: Understanding Total ESAL is crucial for scheduling maintenance and repairs to ensure road safety and longevity.
- **Traffic Analysis**: The components of the equation offer a nuanced view of traffic patterns, which is vital for accurate assessments.

A geo-database model of Jazan's road network was constructed using ArcGIS 10.4. Table 7 and Figure 8 provide detailed descriptive information regarding the characteristics of the city's roads [54]. Supporting the Jazan City Road Geodatabase, **Figure 12**presents the statistical analysis of the road network using ArcGIS 10.4. Furthermore, the Kingdom of Saudi Arabia is advancing rapidly in alignment with Vision 2030, driven by the expansion of its road network in Jazan City.

Figure 13illustrates the map of lanes and locations on the road.

Volume values and construction material prices are utilized to determine the overall cost of optimal route design per layer; however, these figures vary based on topography, road centerline, and design specifications. The overall cost of one kilometer of the study road is summarized in **Table 15** and **Figure 14,** estimated at 1,233,706.17 SR, which includes the cost of materials, equipment, labor, and material testing.

V. CONCLUSIONS

The current study concludes that a Comprehensive Spatial Data Framework (CSDF) for road spatial data is essential. A spatial and descriptive data framework that effectively utilizes open-source data, direct survey measurements, and GIS tools for road construction and maintenance can be used to update Jazan City's CSDF. Ultimately, this CSDF will benefit the community by optimizing maintenance efforts, enhancing road safety, monitoring road conditions, and improving urban infrastructure planning. The study demonstrated the feasibility of compiling a comprehensive assessment of the roads in Jazan City by integrating soil test findings and design using Civil 3D and Geographic Information Systems (GIS). Additionally, similar objectives were achieved in studies conducted by [55-57]. Furthermore, the numerous models created for highways will support future infrastructure research.

The challenges faced in this study were addressed, leading to the following conclusions:

a. A comprehensive Spatial Data Framework (CSDF) to support road design and a geo-database model for routine (periodic) maintenance using GIS and open-source data.
b. The CSDF was utilized to emphasize traffic management optimization, improve maintenance efficiency, and enhance road safety.
c. Collaboration with municipal authorities, transportation planners, civil engineers, and local communities to gather data; was identified;
d. By combining open-source software such as AutoCAD Civil 3D,QGIS, a geodatabase of the road network, site visits, GPS data, traffic data, soil data, and experienced staff, the CSDF will be developed and updated.
e. Volume calculation methods were compared to minimize the costs of road construction and maintenance in Jazan City.
f. A holistic approach to the Comprehensive Spatial Data Framework (CSDF) was established by integrating advanced software, geographical data, and soil analysis, providing a thorough framework

for understanding the distinct geographical and geological context of Jazan is provided,

g. Optimized Road Design: With the aid of accurate modeling facilitated by Civil 3D, the road design was improved, enhancing road longevity and safety.
h. The cost of the study road in Jazan City was calculated and estimated at 1,233,706.17 SAR per kilometer, accounting for the total costs of materials, equipment, labor, and material testing.

VI. SUGGESTIONS FOR FUTURE WORK

Figure 15 outlines the suggestion of Intelligent Transportation Systems (ITS). This system comprises eight components: a control center, a monitor screen, traffic information, data message transmission, data storage and analysis devices, traffic dispatch, and traffic signal adjustments. The author recommends establishing the ITS to support the Comprehensive Spatial Data Framework (CSDF) in the Jazan road network to enhance traffic management, safety, and transportation efficiency. Moreover, numerous benefits can be gained from ITS:

a. Dynamic Lane Management
b. Connected Vehicle Technologies
c. Smart Traffic Signs
d. Comprehensive Incident Detection Systems
e. Mobile Ticketing and Fare Collection
f. Predictive Traffic Modeling
g. Bicycle and Pedestrian Safety Systems
h. Freight Traffic Management Solutions
i. Enhanced Public Transport Real-Time Tracking
j. Integrated Emergency Management Systems

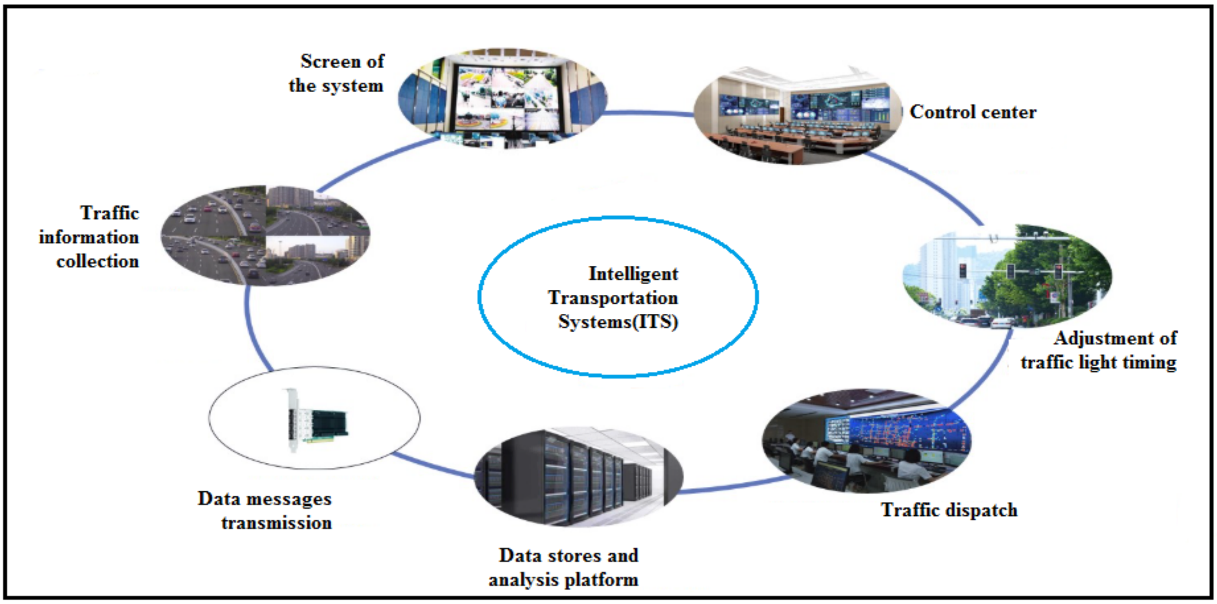

FIGURE 15. Components of Intelligent Transportation Systems (ITS) in Jazan City.

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