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Simulation and Modeling Programs for Electric and Hybrid Vehicles: A Review and Case Study of AVL Cruise for Energy Consumption Analysis

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Abstract Continuous advancements in alternative drive technologies for vehicles necessitate the development of sophisticated computational tools. Due to the inherent complexity of these systems, prototyping can be a time-consuming and expensive endeavour. Fortunately, computer-aided modelling and simulation environments offer a viable alternative by enabling the virtual testing of novel drivetrain solutions without the need for physical prototypes. These environments leverage existing solutions and readily available models of vehicles, drives, and their components, fostering the efficient development of new concepts and optimized drivetrain models. This paper presents a curated overview of select vehicle modelling and simulation programs, followed by the introduction of an electric vehicle model developed within the AVL Cruise software.

Keywords electric vehicle, modelling, simulation, energy efficiency, AVL Cruise

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1. Introduction

This contemporary automotive industry presents engineers and scientists with a continuous stream of novel challenges. The imperative to achieve greater energy efficiency, minimize exhaust emissions, and ensure the comfort and safety of vehicle occupants necessitates the implementation of increasingly sophisticated technological solutions. In this context, computer programs and environments have assumed a critical role, becoming indispensable tools for both automotive enterprises and researchers.

Electric and hybrid vehicles, in particular, undergo continuous advancements. The development of energy storage and electric drive technologies fosters improved efficiency across diverse driving conditions and geographic regions, as evidenced in relevant literature [1,2]. However, manufacturer-provided range and average energy consumption figures may not always translate directly to real-world scenarios. These parameters exhibit variability contingent upon usage patterns, as corroborated by research [3,4]. From a user standpoint, an electric vehicle should exhibit unwavering reliability under all circumstances. Furthermore, range information should be presented with utmost clarity to facilitate effective route planning by drivers.

Evaluating the influence of driving conditions on an electric vehicle's energy consumption and range necessitates the execution of real-world testing procedures. This entails subjecting the vehicle to a battery of tests conducted across diverse terrain types, along varied routes, and incorporating a spectrum of driving styles, as documented in extant research [5-8]. The paramount objective of these tests is to generate significantly more precise data pertaining to the range and energy consumption that can be realistically anticipated under commonplace driving circumstances.

An alternative approach to investigating the influence of driving conditions on energy consumption and range lies in the utilization of simulation studies. This methodology entails the development of a mathematical model specifically tailored to the vehicle under examination [9]. Alternatively, dedicated vehicle simulation software can be employed, enabling the manipulation of vehicle parameters and its drive system [10, 11]. To ensure the veracity of the simulations, it is imperative that they incorporate real-world driving conditions. Many simulation programs utilize speed profiles as a function of time or distance to represent traffic conditions. Additionally, other relevant factors, such as ambient temperature and road elevation, can be integrated into the simulations.

The field of scientific literature dedicated to hybrid and electric vehicle modelling boasts a plethora of publications showcasing diverse tools and the resultant vehicle models [12-14].

Beyond intricate descriptions of the models themselves, numerous studies incorporate simulation results, furnishing comprehensive data on fuel/energy consumption, emissions of harmful exhaust components, and the efficiency of individual drive system components across a spectrum of driving conditions. These computer simulations facilitate the estimation of anticipated exhaust emissions and other pollutants generated by the vehicle, a critical aspect for environmental safeguarding and adherence to emission regulations.

The functionalities provided by contemporary simulation programs transcend the realm of mere fuel consumption analysis. These programs have evolved into formidable instruments that facilitate the execution of holistic simulation studies encompassing a multifaceted spectrum of aspects pertinent to vehicle operation, as documented in the extant research [15-17]. Computer simulations empower researchers to pinpoint the origins of vibrations and noise generated by the vehicle, subsequently enabling the development of design and technological solutions geared towards their mitigation. Additionally, they permit the evaluation of the vehicle's performance in terms of acceleration, hill-climbing capabilities, and the attainment of maximum speed. Simulation studies play a pivotal role in the precise prediction of fuel consumption under a multitude of driving conditions. This, in turn, paves the way for the optimization of both vehicle and drive system design with a focus on energy efficiency, culminating in demonstrably reduced fuel consumption and emissions.

Computer simulations stand as an exceedingly valuable instrument within the process of testing and validating drive system components and other vehicular elements, as corroborated by extant research [21, 22]. Their implementation serves to demonstrably expedite the research and development process while concurrently mitigating testing expenditures. By leveraging simulation programs, researchers are empowered to conduct preliminary assessments and analyses of novel design concepts and technological solutions prior to the commencement of prototyping and physical testing phases. This proactive approach facilitates the identification of potential shortcomings at an early juncture of the project, enabling their rectification and the optimization of the design itself [23, 24].

It is imperative to acknowledge that computer programs and environments do not supplant empirical research entirely. Nevertheless, they constitute exceedingly valuable tools that demonstrably reduce research time and expenditures. Furthermore, they offer the potential to glean information that may be inaccessible or arduous to obtain through laboratory experiments or field tests.

The present paper endeavours to furnish a concise analysis of the functionalities resident within select programs designed for the simulation and modelling of electric and hybrid vehicles. Additionally, it presents an illustrative example of the AVL Cruise program's application in analysing the energy consumption of an electric vehicle. This article serves as a valuable repository of information for scientists and engineers engaged in the design and development of electric and hybrid vehicles. The analysis of the capabilities offered by select simulation and modelling programs can facilitate the judicious selection of appropriate software tailored to specific project requirements. Moreover, the example of utilizing AVL Cruise for electric vehicle energy consumption analysis has the potential to serve as a catalyst for further research in this domain.

The first section of the article embarks upon a discussion of various types of simulation and modelling programs employed for vehicles, delving into their capabilities and the computational procedures they utilize. Subsequently, a particular simulation study of an electric vehicle, realized using the AVL Cruise program, is presented. The following section of the paper furnishes the simulation results, encompassing statistical parameters pertaining to energy consumption, recovered energy, and depth of discharge (DOD). Additionally, it explores the relationships between energy consumption parameters and select route parameters. The concluding portion of the article delves into a discussion of the obtained results and formulating conclusions of the research.

2. Analysis of capabilities of selected programs for vehicle simulation and modeling

Currently, there are numerous programs available for vehicle simulation and modelling, each offering diverse functions and capabilities. The choice of appropriate software depends on the specific needs of the user, budget considerations, and the scope of work. There exists a wide range of mathematical models and simulation programs designed for vehicle research. Each of these tools provides different functionalities and capabilities, making the selection of the right tool dependent on the specific requirements of the user.

Simulation programs leverage mathematical models to calculate and predict vehicle behaviour. These model-based programs play a pivotal role in the design, development, and testing phases of hybrid and electric vehicles. Employing complex mathematical equations, they simulate the intricate interactions between various vehicle components, including internal combustion engines, electric motors, drivetrain systems, batteries, and control systems. These simulations empower engineers to assess vehicle performance metrics, predict energy consumption and emissions levels, and identify potential design flaws before physical prototypes are constructed. Prominent examples of such programs include AVL Cruise and Ansys Powertrain, alongside numerous proprietary simulation tools developed by researchers, as evidenced in [25- 27].

To achieve this level of detail, contemporary vehicle simulation programs draw upon a diverse arsenal of mathematical models, each meticulously crafted to replicate the intricate behaviours of vehicles under various operating conditions. The selection of the most appropriate model hinges on the specific needs and objectives of the simulation being conducted.

Simulation programs that leverage linear models hinge on the fundamental assumption of proportional relationships between input and output variables. In essence, this translates to a change in the value of one variable inducing a directly proportional change in the value of another. While these streamlined models prove to be instrumental in analysing fundamental vehicle behaviours such as speed, acceleration, and braking, their inherent simplification of reality

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necessitates limitations in their application. They are best suited for straightforward phenomena. When confronted with more intricate problems, the utilization of more sophisticated nonlinear or hybrid models becomes indispensable to achieve results characterized by a demonstrably higher degree of accuracy and reliability.

Simulation programs that using nonlinear models transcend the inherent limitations of their linear counterparts by incorporating intricate, nonlinear relationships between input and output variables. These sophisticated models provide a significantly more nuanced reflection of reality, enabling the analysis of phenomena that are beyond the grasp of linear models alone. By meticulously accounting for the interactions among various vehicle components, such as the engine, drivetrain, aerodynamics, and suspension, nonlinear models facilitate a demonstrably more accurate representation of the object under study.

Consequently, nonlinear models offer superior fidelity in simulating real-world vehicle behaviour, making them the preferred choice for analysing complex phenomena. However, this enhanced accuracy comes at the cost of increased complexity in both development and implementation. Successfully utilizing these models necessitates a more profound expertise in mathematics and modelling techniques.

The realm of simulation programs extends to the utilization of hybrid models, which strategically combine characteristics from distinct model types, such as linear and nonlinear models. These multifaceted models are adept at tackling complex phenomena that necessitate consideration of both straightforward and intricate relationships between variables.

Illustrative examples of their application encompass the analysis of energy consumption and exhaust emissions under a multitude of driving conditions. Additionally, they prove instrumental in analysing vehicle behaviour while traversing uneven terrain, meticulously accounting for the vehicle's interactions with the environment. Hybrid models flourish in scenarios demanding a comprehensive understanding of the system's behaviour. They achieve this by judiciously incorporating the advantages of both linear simplicity and nonlinear fidelity, as dictated by the specific objectives of the simulation. This synergistic approach fosters a more nuanced and accurate representation of real-world dynamics, demonstrably surpassing the capabilities of purely linear or nonlinear models employed in isolation.

The many of vehicle simulation programs is further enriched by the inclusion of quasi-static models. These models hinge on the fundamental assumption that specific variables, such as engine rotational speed, exhibit a gradual rate of change compared to other variables within the system. Their primary application lies in the analysis of energy consumption and exhaust emissions, as exemplified by their implementation in programs like PSAT. While offering demonstrably faster computational speeds relative to dynamic models, quasi-static models are inherently unsuited for the analysis of dynamic vehicle behaviours. Their domain of expertise lies primarily in simulating vehicle statics, encompassing the analysis of vehicle behaviour at rest or under low-speed conditions. They can be incorporated into vehicle dynamics simulations, but their applicability is limited to straightforward manoeuvres such as braking or accelerating along a straight line.

Dynamic models stand in stark contrast to their static counterparts by explicitly describing a vehicle's behaviour as it unfolds over time. This entails meticulously accounting for the variations in forces and accelerations that the vehicle experiences. Their core competency lies in analysing the vehicle's dynamic movements, encompassing manoeuvres such as acceleration, braking, cornering, and traversing uneven terrain. While offering a significantly richer tapestry of results compared to static models, dynamic models necessitate a corresponding increase in both computational time and power. This stems from their comprehensive incorporation of all relevant variables and their dynamic fluctuations. Consequently, they are ideally suited for tackling the most intricate phenomena, such as the realm of vehicle dynamics.

Dynamic models reign supreme in the domain of vehicle dynamics simulation, meticulously capturing the vehicle's behaviour throughout the course of motion. Their applicability extends beyond this domain, and they can also be incorporated into vehicle statics simulations, albeit under circumstances characterized by complex loading conditions. Notably, dynamic models play an indispensable role in simulations of electric and hybrid vehicles. This is due to their remarkable ability to represent the intricate phenomena that manifest during driving conditions. Programs such as PSIM and Virtual Test Bed (VTB) exemplify the utilization of dynamic models in this context.

Beyond the realm of model-based simulation programs, data-driven approaches offer an alternative path for simulating hybrid and electric vehicles. These programs leverage real-world test data and measurements to construct simulations of vehicle behaviour under diverse driving conditions. Illustrative examples of such programs include SimPowerSystem/SimDriveline, ANSYS Simplorer, and PSIM.

The efficacy of this approach is further corroborated by the burgeoning body of research that utilizes physics-based simulation models for vehicles, as evidenced by works documented in [28, 29]. Physics-based simulation programs are rapidly gaining traction within the field of vehicle simulation, presenting several compelling advantages over traditional model-based approaches. These programs leverage real-world data to construct simulations of vehicle behaviour, potentially leading to enhanced accuracy, particularly in intricate scenarios. This is because physics-based simulations directly incorporate the complexities of real-world physics, which may not be fully captured by traditional mathematical models.

Furthermore, physics-based simulations can often achieve faster execution speeds compared to programs that rely on complex mathematical models. This stems from the fact that they bypass the need to solve intricate mathematical equations, streamlining the simulation process. Additionally, their implementation is generally simpler as it avoids the time-consuming development of complex mathematical models.

Hybrid simulation programs carve out a niche by offering distinct advantages over purely model-based or physic-based approaches. This strategic marriage of methodologies fosters enhanced simulation accuracy by capitalizing on the strengths of both paradigms. It leverages the theoretical underpinnings embedded within models while simultaneously incorporating the practical insights gleaned from real-world test data. Additionally, hybrid programs can potentially achieve faster computational speeds. This efficiency stems from the ability of data to streamline certain calculations that would otherwise be required by complex models. User-friendliness emerges as another benefit, as these programs often do not necessitate profound expertise in intricate mathematical models.

However, it would be remiss not to acknowledge the inherent drawbacks associated with hybrid programs. Their implementation complexity presents a significant hurdle, as it necessitates the meticulous integration of mathematical models with real-world test data. Furthermore, they may exhibit limitations in flexibility. Modifying simulations to accommodate novel conditions or components can be a more intricate undertaking compared to purely model-based or physic-based programs.

Vehicle simulation programs primarily employ three distinct computational approaches: the forward-facing method, the backward-facing method, and a hybrid method that merges both. The forward-facing method aligns its computations with the direction of power transmission. Initiating with a specified value (often an acceleration signal), it calculates the requisite torque for each drivetrain component, meticulously following the power flow through each subsystem until the desired vehicle speed is attained [30, 31]. This method hinges on physical equations and the dynamic interactions between drivetrain components. However, the presence of intricate feedback loops and control algorithms necessitates computationally intensive calculations. Despite this drawback, the forward-facing method has proven valuable in developing vehicle models, as evidenced by its application in research studies [32] and programs like PSAT/Autonomie.

The backward-facing method stands in stark contrast to its forward-facing counterpart. Here, computations progress in the opposite direction of power transmission. This method begins with a specified driving cycle's speed profile. Based on this, the requisite wheel power is estimated and meticulously propagated back through each drivetrain component, ultimately reaching the energy source. Notably, the backward-facing approach treats each drive element as an independent module. This characteristic facilitates rapid calculations for both straightforward and intricate models. Additionally, it allows for the seamless integration of lookup tables or performance maps, circumventing the need to model every physical phenomenon. Consequently, this method yields demonstrably faster results compared to the forward-facing method. The application of the backward-facing method is exemplified by the construction of vehicle models documented in the study [33] and programs like GT SUITE and Simplev (Simple Electric Vehicle Simulation).

The mixed procedure merges the strengths of both the forward-facing and backward-facing methods. It commences with calculations performed using the backward-facing approach. This initial stage facilitates the estimation of efficiency values and operating limits for the model's subsystems. Subsequently, armed with these known values, the procedure transitions to the forward-facing method to compute power and energy values from the energy source all the way to the wheels.

However, the primary drawback associated with the mixed approach lies in the necessity of maintaining two distinct models for the same component [34]. Despite this limitation, the mixed procedure has found application in constructing vehicle models for programs such as AVL Cruise, PSIM, and ADVISOR.

Vehicle modelling and simulation programs have become invaluable tools in the research and development of electric and hybrid vehicles. Their application significantly accelerates the innovation cycle, paving the way for the introduction of novel technologies and, ultimately, more efficient and environmentally responsible vehicles. These computer programs offer a powerful testing environment, enabling researchers to rapidly and cost-effectively evaluate a multitude of vehicle configurations under diverse driving conditions. This virtual testing ground fosters the optimization of vehicle designs, leading to demonstrably improved performance metrics. Furthermore, simulation programs have the remarkable capability to predict vehicle behaviour in scenarios that would be impractical or even unsafe to replicate in real-world testing.

3. Simulation study of an electric vehicle using AVL Cruise software

This investigation aims to leverage a vehicle modelling and simulation program to analyse the energy consumption of an electric vehicle (EV) within an urban driving environment. To achieve this objective, an EV model was constructed within the AVL Cruise software. Subsequently, twenty-one real-world urban driving speed profiles were incorporated into the program.

The simulation results were then employed to analyse the following parameters:

- total energy consumption per kilometre (kJ/km),
- depth of Discharge (DOD) of the battery (%),
- recovered energy per kilometre (kJ/km),

The data underwent a statistical analysis to determine the average values, medians, and distribution patterns of the aforementioned energy consumption parameters.

3.1. AVL Cruise overview

The AVL Cruise program facilitates the modelling and simulation of vehicles equipped with diverse powertrain configurations. Within the program, the vehicle model is represented as a system comprised of interconnected subsystems, encompassing both vehicle and powertrain components. AVL Cruise offers a comprehensive suite of capabilities, enabling users to:

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- generate reliable and precise predictions of fuel consumption for vehicles under development;
- conduct a thorough analysis of energy flow, power distribution, and powertrain system losses, tracing the path from the power source to the wheels;
- optimize the powertrain for a balance between fuel efficiency, minimized harmful exhaust emissions, and desired vehicle traction properties;
- perform an in-depth analysis of torsional vibrations within flexible chassis structures under dynamic load conditions;
- investigate the thermal distribution across powertrain components.

The AVL Cruise program empowers users to leverage an extensive library of real-world vehicles and powertrain components during the vehicle modelling process. This library encompasses a comprehensive set of parameters and characteristics for each component.

The model development process commences with the selection of the target vehicle type. AVL Cruise offers a comprehensive selection, including passenger cars, buses, trucks, and motorcycles. Subsequently, the user chooses the appropriate powertrain configuration from a range of options including conventional, electric, series and parallel hybrid, dual-engine systems, and advanced transmission systems.

In the following steps, users can meticulously specify the parameters of each powertrain component and define the energy management strategy. The program facilitates customization through an intuitive interface; users can access and modify individual parameters by clicking on the corresponding blocks within the vehicle model.

The program further extends its functionality by allowing users to incorporate additional devices, such as air conditioning or electric power steering systems, into the vehicle model. This enables the simulation to account for the impact of these auxiliary systems on vehicle performance.

External factors can also be integrated into the simulation process. Users have the option to select from a range of predefined factors, including wind force, ambient temperature, and road surface conditions. Alternatively, users can define their own custom parameters for these factors.

To complete the model setup, the program offers a selection of built-in driving cycles, catering to various driving scenarios. Users can also import custom driving cycles or utilize the program's capability to generate random cycles that represent urban, suburban, or highway driving conditions.

The simulation leverages a combined backward/forward computational approach. This methodology facilitates a more efficient and accurate assessment of how input parameter values influence the performance of powertrain components. The program calculates all possible combinations of these variables.

Upon simulation completion, users are presented with a comprehensive set of results. This includes fuel consumption values, emission levels, vehicle performance metrics, maximum grade climbing capability, and acceleration times. Additionally, the program generates graphs and characteristics that depict the operational behaviour of the powertrain components. The results are presented in a user-friendly format, incorporating both graphs and tables.

By leveraging the simulation results generated by AVL Cruise, users can conduct comparative analyses of performance parameters, powertrain efficiency, and fuel consumption across various powertrain configurations under defined driving conditions. This facilitates informed decision-making during the vehicle development process.

3.2. Electric vehicle model in AVL Cruise

This section details the specifications of the electric vehicle (EV) chosen for the simulation. The EV is a front-wheel drive configuration, as depicted schematically in Figure 1 within the AVL Cruise program.

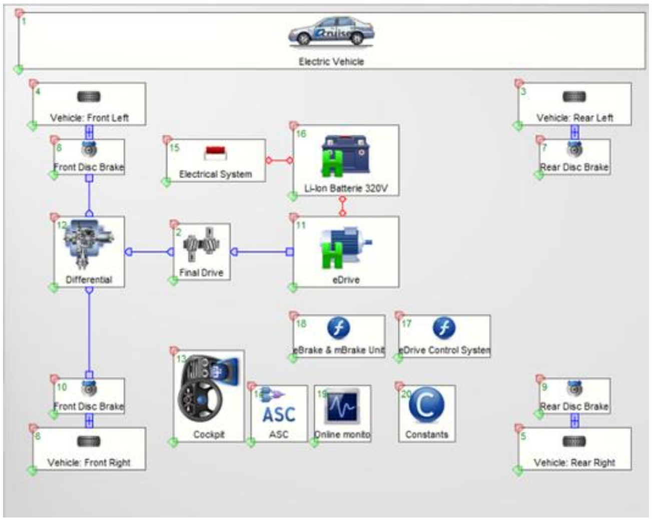

Figure 1. A sample schematic diagram of the electric vehicle model in AVL Cruise

The vehicle possesses a wheelbase of 2467 mm and a centre of gravity positioned at a height of 500 mm. The curb weight of the vehicle is 1200 kg, with a maximum gross weight of 1580 kg. Notably, the vehicle is equipped with an energy recuperation system that captures energy during braking processes.

The braking system comprises disc brakes on all four wheels. The front brake discs possess a larger diameter (1800 mm) compared to the rear discs. The vehicle's frontal area is measured at 1.97 m². A lithium-ion battery with a fully charged energy capacity of 10 Ah is integrated into the vehicle. Both the battery and the electric motor operate at a nominal voltage of 320 V. The minimum and maximum permissible voltage ranges are 220 V and 420 V, respectively. Table 1 summarizes the key parameters of the electric vehicle.

Table 1. Electric vehicle specifications

Parameter	Value
Height of centre of gravity [mm]	500
Wheelbase [mm]	2467
Frontal area [m²]	1.97
Mass [kg]	1350
Battery energy capacity [Ah]	10
Battery state of charge [%]	100
Nominal voltage [V]	320

3.3. Test drives

This investigation employed a GPS system to collect data for twenty-one (21) individual trips within the central area of a medium-sized city. Each trip consisted of a 5 km route. Urban driving environments are typically characterized by frequent stopping, accelerating, maintaining constant speeds for short durations, and braking manoeuvres. Table 2 summarizes the statistical parameters of these trips, which were subsequently used in the simulation.

Table 2. Overview of selected test drive parameters

	Duration of the test drive [s]	Maximum speed [km/h]	Average speed [km/h]	Maximum acceleration [m/s²]	Maximumum deceleration [m/s²]
Min	574.00	47.10	9.94	1.80	1.90
Max	1889.91	66.02	30.9	3.63	8.87
Mean	955.24	53.66	21.07	2.65	3.56
Median	853.47	52.26	21.23	2.91	3.07
Standard deviation	371.58	4.34	6.20	0.42	1.62
Coefficient of variation	39%	8%	29%	16%	45%

The analysis of the collected data revealed a range of maximum vehicle speeds across the trips. The highest recorded value was 66.02 km/h, while the lowest was 47.10 km/h. The median maximum speed, which represents the middle value when the data is ordered from lowest to highest, sits at 52.26 km/h. Similarly, the median average speed across the trips was determined to be 21.23 km/h. Notably, the maximum vehicle acceleration experienced during the trips reached 3.63 m/s², while the maximum deceleration event registered 8.82 m/s².

3.4. Simulation results

This chapter delves into a detailed analysis of selected energy consumption parameters for an electric vehicle, drawing upon the data presented in Table 3. The analysis encompasses parameters such as Depth of Discharge (DOD), total energy consumption, and recovered energy. This investigation aims to evaluate and quantify the energy efficiency of the electric vehicle.

Table 3. Overview of selected energy consumption parameters

	DOD [%]	Energy recovered from braking [kJ/km]	Total energy consumption [kJ/km]
Min	3.34	0.47	0.05
Max	4.67	0.70	0.14
Mean	3.80	0.54	0.08
Median	3.67	0.51	0.07
Standard deviation	0.39	0.07	0.03
Coefficient of variation	10%	13%	33%

The analysis of total energy consumption revealed a variability ranging from 0.47 kJ/km to 0.70 kJ/km. The average energy consumption across the trips was determined to be 0.54 kJ/km, while the median value, representing the central point when the data is ordered from lowest to highest, sits at 0.51 kJ/km. The standard deviation for this parameter is 0.07 kJ/km, resulting in a coefficient of variation of 13%. This moderate level of variability suggests the presence of diverse driving conditions during the analysed trips. Potentially, these varying conditions could influence the vehicle's energy efficiency. Figure 2 visually explores the relationship between total energy consumption per kilometre and trip duration, average speed, maximum acceleration, and maximum deceleration experienced during the analysed trips.

Energy consumption per kilometre directly reflects the energy efficiency of the electric vehicle under varying driving conditions. This investigation analysed the influence of route-related parameters on energy consumption through simulation studies. As illustrated in Figure 2a, a positive correlation was observed between trip duration and energy consumption. This suggests that the vehicle's energy expenditure increases with longer travel times.

The relationship between average travel speed and energy consumption per kilometre for the electric vehicle exhibits an inverse trend, as depicted in Figure 2b. At lower speeds (below 10 km/h), energy consumption demonstrates greater

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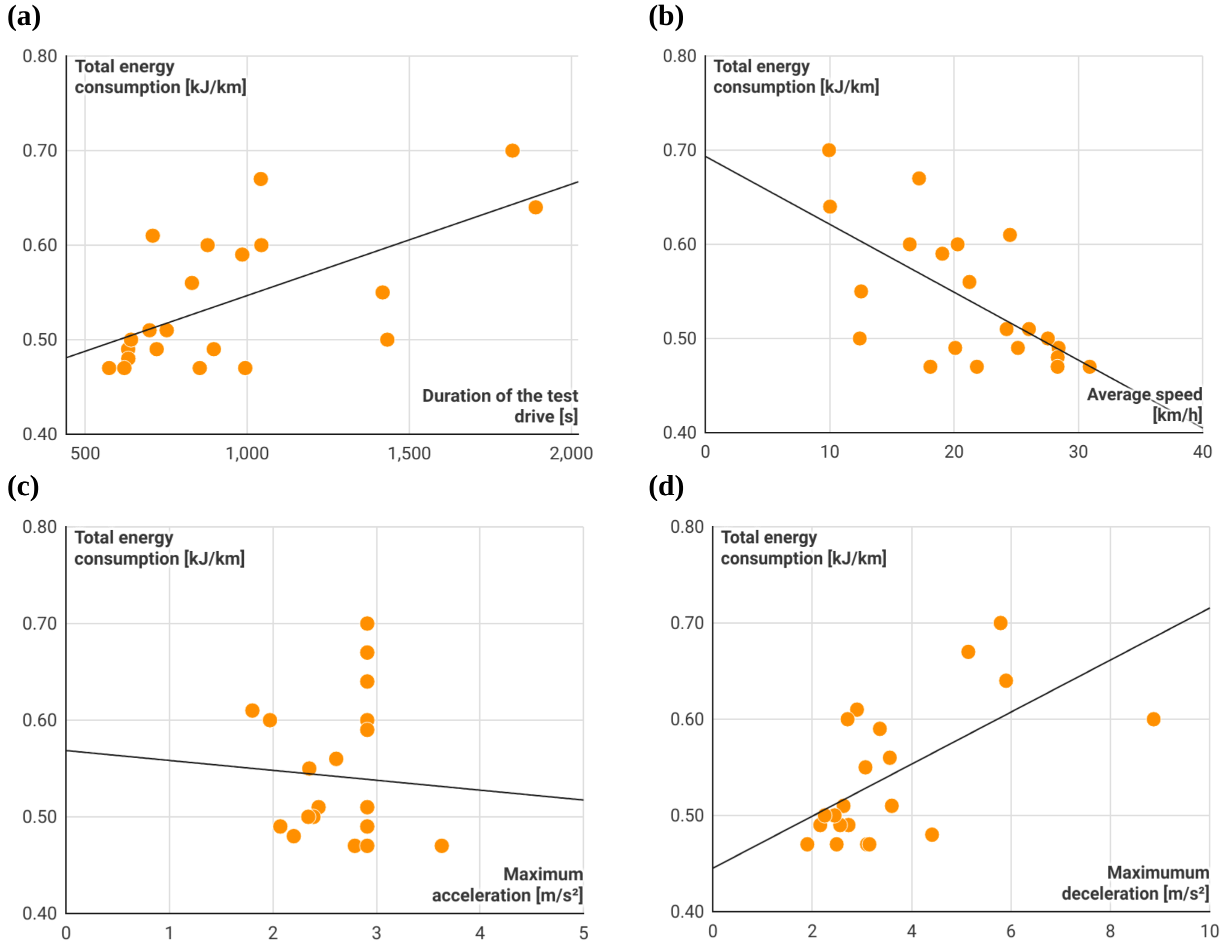

Figure 2. Total energy consumption in relation to (a) trip duration, (b) average speed, (c) maximum acceleration, and (d) maximum deceleration in the analyzed trips

variability, with some data points exceeding 0.60 kJ/km. Conversely, at speeds exceeding 20 km/h, energy consumption appears more consistent, typically reaching values around 0.50 kJ/km or lower. This suggests that smoother travel with fewer stops translates to lower energy consumption.

An examination of the impact of maximum acceleration n energy consumption revealed a relatively scattered distribution of data points around the trend line, as shown in Figure 2c. The most significant dispersion of points occurs within the range of 2 to 3 m/s² for maximum acceleration, where energy consumption exhibits values between 0.50 kJ/km and 0.70 kJ/km. This finding suggests that maximum acceleration has a minimal influence on the overall energy consumption of the electric vehicle.

Conversely, the analysis of the relationship between electric energy consumption and maximum deceleration in the electric vehicle demonstrates a positive correlation, as depicted in Figure 2d. At lower maximum deceleration values, energy consumption remains relatively constant, ranging from 0.47 kJ/km to 0.51 kJ/km. However, with increasing maximum deceleration, energy consumption also begins to rise noticeably, particularly for values exceeding 3.56 m/s². This trend suggests that abrupt braking manoeuvres may lead to higher energy losses due to a potential decrease in the efficiency of the vehicle's energy recuperation system.

The Depth of Discharge (DOD), a parameter that signifies the extent to which the battery's capacity is utilized during operation. The DOD values for the analysed trips range from 3.34% to 4.67%. The average DOD across the trips was determined to be 3.80%, with a median of 3.67%. The standard deviation for this parameter is a mere 0.39%, resulting in a coefficient of variation of 10%. This minimal variability in DOD indicates stable battery energy management strategies employed during the simulations. This stability is advantageous for both the vehicle's energy efficiency and the lifespan of the battery itself. Figure 3 visually depicts the relationship between DOD and trip duration, average speed, maximum acceleration, and maximum deceleration experienced during the analysed trips.

The depth of discharge indicator serves as a valuable metric for assessing the energy demands placed upon an electric vehicle's battery. As illustrated in Figure 3a, a positive correlation exists between trip duration and DOD. This trend is logical, as longer driving times necessitate greater energy consumption, leading to a higher DOD. Average vehicle speed also exerts an influence on DOD. As depicted in Figure

3b, higher average speeds typically translate to increased energy consumption, consequently resulting in a higher DOD.

The impact of maximum acceleration on DOD exhibits some variation, as shown in Figure 3c. The observed scatter in DOD values across different levels of maximum acceleration suggests that the intensity of acceleration plays a role in energy consumption. Lower acceleration values correspond to lower energy consumption and a lower DOD. Conversely, higher acceleration demands more energy, leading to increased energy consumption and a higher DOD. A clear and direct relationship was observed between maximum deceleration and DOD, as shown in Figure 3d. Generally, higher maximum deceleration values tend to coincide with an increase in DOD.

Conventional vehicles dissipate kinetic energy as heat during braking, resulting in an irreversible loss. In contrast, electric and hybrid vehicles possess the ability to recapture a portion of this kinetic energy and utilize it to power the electric motor. This process, known as regenerative braking, significantly contributes to the energy efficiency of electric vehicles.

The analysis of the analysed trips revealed that recovered energy during driving ranged from 0.05 kJ/km to 0.14 kJ/km, with an average of 0.08 kJ/km and a median of 0.07 kJ/km. The standard deviation was calculated to be 0.03 kJ/km, resulting in a coefficient of variation of 33%. This higher level of variability, compared to other analysed parameters, suggests that the effectiveness of the vehicle's energy recovery system is largely influenced by specific driving conditions. These conditions may include factors such as vehicle speed, terrain topography, and driver behaviour.

Figure 4 visually explores the relationship between recovered energy per kilometre and trip duration, average speed, maximum acceleration, and maximum deceleration experienced during the analysed trips.

Urban driving environments, characterized by frequent stops and starts, present ideal conditions for the regenerative braking system employed in electric vehicles. As illustrated in Figure 4a, the analysis of simulation results for an electric vehicle in various urban trips revealed a trend of higher recovered energy with increasing trip duration.

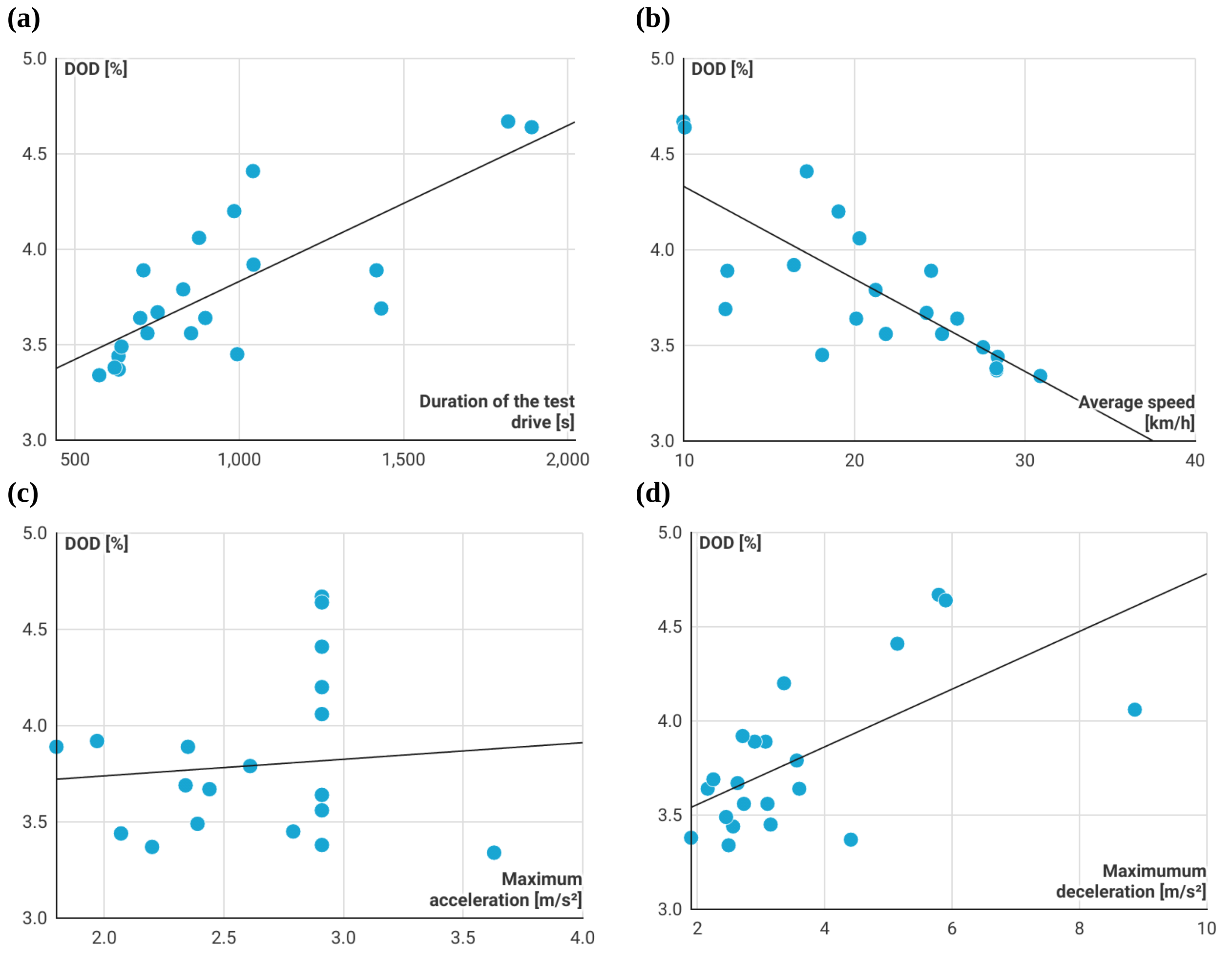

Figure 3. DOD in relation to (a) trip duration, (b) average speed, (c) maximum acceleration, and (d) maximum deceleration in the analyzed trips

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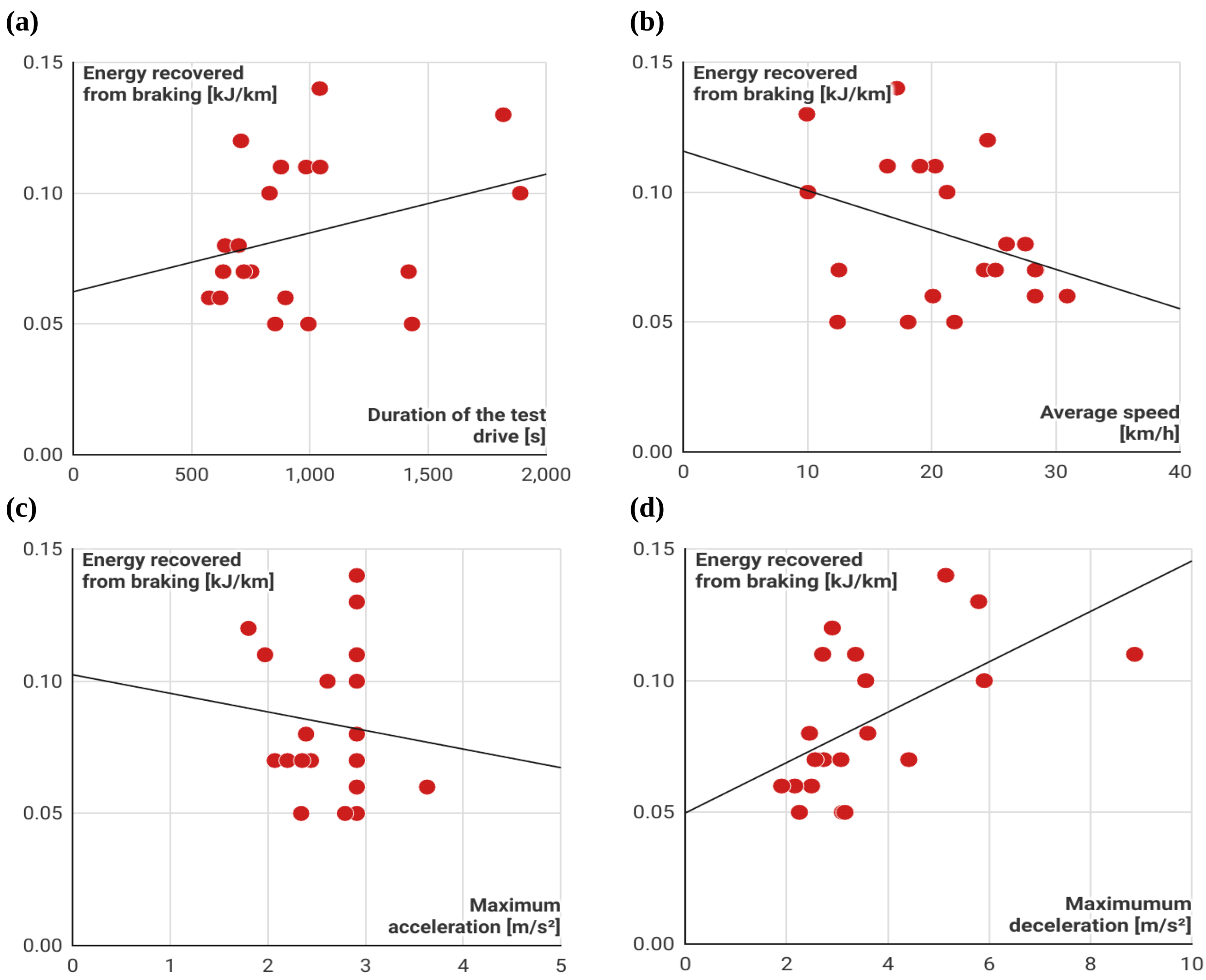

Figure 4. Energy recovered from braking in relation to (a) trip duration, (b) average speed, (c) maximum acceleration, and (d) maximum deceleration in the analyzed trips

This logical observation can be attributed to the increased number of braking opportunities encountered during longer trips within urban settings.

An inverse relationship exists between average vehicle speed and recovered energy, as depicted in Figure 4b. Lower average speeds generally correspond to higher recovered energy values. This trend likely stems from the more frequent braking events and reduced driving dynamics typically associated with urban traffic conditions.

The influence of maximum acceleration on recovered energy exhibited no clear pattern, as shown in Figure 4c. Low recovered energy values (0.05 - 0.07 kJ/km) were observed across a range of acceleration levels, including both low (2.07 m/s^2) and high (3.63 m/s^2) values. Similarly, higher recovered energy values (0.10 - 0.14 kJ/km) did not demonstrate a consistent correlation with maximum acceleration, appearing at various acceleration levels from 1.8 m/s^2 to 2.91 m/s^2.

In contrast, a clear and positive relationship was identified between maximum deceleration experienced during trips and the amount of energy recovered through braking, as shown in Figure 4d. This finding confirms that more intense braking manoeuvres enhance the efficiency of the vehicle's energy recuperation system.

4. Discussion and conclusions

This paper presents a concise analysis of select software programs employed in the simulation and modelling of electric and hybrid vehicles. Additionally, it exemplifies the application of AVL Cruise software in analysing the energy consumption of an electric vehicle.

A multitude of software programs are available for vehicle simulation and modelling, each distinguished by its unique functionalities and capabilities. The selection of the most suitable software hinges upon a careful consideration of user requirements, budgetary constraints, and the specific scope of the project. Broadly categorized, model-based simulation programs leverage mathematical models to predict vehicle behaviour. Conversely, physics-based simulation programs rely on real-world test data and measurements to replicate vehicle performance under diverse driving conditions. Hybrid programs, as their name suggests, integrate elements from both approaches.

The application of vehicle modelling and simulation programs in the development of electric and hybrid vehicles offers significant advantages. These programs can substantially accelerate the development process for new technologies, ultimately leading to more efficient and environmentally friendly vehicles. Additionally, they provide the capability to predict vehicle behaviour under conditions that would be impractical or unsafe to replicate in real-world testing.

This study employed the AVL Cruise software to analyse the energy consumption of an electric vehicle operating under urban driving conditions. A digital model of the electric vehicle was constructed within the AVL Cruise environment. Subsequently, twenty-one speed profiles, collected from real-world urban driving scenarios, were implemented into the program. Leveraging the simulation results, the analysis focused on the total energy consumption, Depth of discharge of the battery, and the recovered energy during operation.

The simulation results revealed a range of values for total energy consumption, from 0.47 kJ/km to 0.70 kJ/km, with an average of 0.54 kJ/km. This translates to an average energy expenditure of 0.54 kJ per kilometre travelled by the vehicle. DOD of the battery also exhibited variability, ranging from 3.34% to 4.67%, with an average of 3.80%. This indicates that, on average, the batteries discharged by 3.80% during the analysed driving scenarios. Recovered energy values also varied, with a range of 0.02 kJ/km to 0.11 kJ/km and an average of 0.06 kJ/km. This signifies that the vehicle recovered an average of 0.06 kJ of energy per kilometre travelled during braking events.

Furthermore, the simulations demonstrated the influence of driving factors on energy consumption, DOD, and recovered energy. These factors include trip duration, average speed, maximum acceleration, and maximum deceleration. Increased trip duration, higher average speeds, and greater maximum acceleration values all contributed to higher energy consumption and DOD of the battery. Conversely, higher maximum deceleration resulted in a dual effect: increased energy consumption and DOD while simultaneously decreasing recovered energy.

The application of AVL Cruise software, as exemplified in the analysis of an electric vehicle's energy consumption, serves as a compelling illustration of how such programs can yield valuable insights that mirror real-world performance. These insights are instrumental in the development of electric vehicles with superior efficiency and reduced environmental impact.

For researchers and engineers engaged in the design and development of electric and hybrid vehicles, simulation and modelling programs represent invaluable tools. These programs enable comprehensive analysis of various operational aspects of electric and hybrid vehicles, encompassing energy consumption, range, performance metrics, and emission levels. By leveraging simulation results, researchers can optimize vehicle designs and achieve improvements in overall efficiency.

This paper serves as a springboard for further exploration within the field of electric and hybrid vehicle simulation and modelling. Numerous avenues warrant further investigation, including the development of more intricate models for vehicle components, the incorporation of external factors that influence energy consumption, and the creation of optimization methods for vehicle designs based on a multitude of criteria. Continued advancements in these areas will undoubtedly contribute to the ongoing evolution and refinement of electric and hybrid vehicle technologies.

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Impact of Road Transport Determinants on the Distribution of Farm Inputs in Wukari, Taraba State, Nigeria

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Abstract Using a regression analysis and a sample of 200 respondents, this study looks at how factors pertaining to road transport affect the distribution of agricultural inputs in Wukari, Taraba State, Nigeria. The results show that the constant term in the regression model is 12.584, with a statistical significance of 0.000. Holding transport factors constant establishes a baseline distribution of agricultural inputs. With a beta coefficient of 0.191 and a standard error of 0.071, the transport determinants coefficient is 0.193, suggesting that transportation improvements have a moderate yet substantial effect on the distribution of agriculture inputs. With a 95% confidence interval spanning from 0.054 to 0.333, there is a significant association between a one-standard-unit improvement in transport determinants and a 0.193 rise in farm input distribution (at the 0.007 level). Targeted improvements to transportation systems can aid agricultural development in the region, as these results underscore the critical importance of transportation infrastructure in enhancing the efficiency of farm input distribution. Future research could benefit from cross-regional comparisons to put results in perspective, time-series analyses to measure effects, a wider range of variables to account for broader influences, and sophisticated statistical methods to strengthen outcomes. The importance of transportation infrastructure to agricultural logistics and development is crucial, and these suggestions are an attempt to better comprehend and handle this role..

Keywords Transport determinants, Supply Chain, Agricultural, Farm Input, Nigeria

JEL R40, R42, Q10, Q12

1. Introduction

The expansion of road networks worldwide has played a vital role in societal welfare, although its multidimensional significance remains insufficiently explored and understood. Disparities exist across continents regarding the growth and density of road networks. While some countries boast dense road networks, most countries have less dense ones. Road transport networks contribute to job opportunities, income generation, resource exploitation, exchange of goods, and poverty alleviation [7].

Reference [7] posits that roads ensure accessibility, mobility, liveability, activity location, safety, social interaction, dispersal of ideas and services, and land-use efficiency. In developing countries, investment in transport infrastructure is considered essential for economic well-being and national development. Road transport services play a key role in facilitating economic activities, including the distribution of farm inputs

The efficient distribution of farm inputs stands as a cornerstone in bolstering agricultural productivity and fortifying food security within Nigeria and across the globe. The accessibility and quality of road infrastructure on a global scale significantly shape the landscape of farm input accessibility. Robust road networks serve as conduits for the timely delivery of crucial components such as seeds, fertilizers, pesticides, and machinery to farmers. According to reference [7] the interplay between road infrastructure, farm input distribution, economic development, trade dynamics, and market accessibility has far-reaching consequences for agricultural competitiveness and the food production system globally. The importance of road infrastructure for agriculture in Nigeria We cannot overstate the importance of road infrastructure in Africa, where agriculture remains the backbone of many communities. Good road networks are essential for transporting goods and providing inputs across vast rural areas. Unfortunately, the agricultural sector still faces challenges such as poor road maintenance, inadequate connectivity, and limited market access [11].

These transportation issues are particularly significant in Nigeria, one of Africa's leading agricultural producers. Inadequate road networks create obstacles for distributing agricultural inputs, especially in rural regions [11]. The situation in Wukari Local Government Area (LGA) in Taraba State exemplifies these broader challenges. Wukari's agricultural communities rely heavily on road networks to access markets and essential inputs.

According to reference [11] farmers face major difficulties in obtaining inputs and selling their crops due to poor road conditions, high transportation costs, and long travel times. Several factors influence the distribution of agricultural inputs via road transport. These include the quality of roads, the extent of highway networks, transportation hubs, the infrastructure for transporting goods and services, and the frequency of road maintenance.

Deficiencies in any of these areas can negatively impact agricultural productivity [11]. When distributing farm inputs, several factors must be considered, including their efficient use, ease of acquisition, equitable distribution, and the availability of necessary tools, livestock, and fertilizers. Key considerations include the distance between input providers, the reliability of supply networks, and the cost of inputs. The interaction between these factors and road transportation highlights the complex relationship between infrastructure and agricultural outcomes [10]. By comprehensively examining these factors, researchers and policymakers can enhance agricultural development and food security in Nigeria and other countries. Addressing road transport issues is crucial for the efficient distribution of farm inputs [7].

Reference [10] emphasize that in Nigeria, where agriculture significantly contributes to the economy, improving agricultural production and ensuring food security depend on the efficient distribution of agricultural inputs. However, the current state of road infrastructure severely hampers this process, particularly in regions like Wukari. Nigeria needs a well-developed road network to transport agricultural inputs quickly and affordably from rural areas to production zones and markets. Unfortunately, the reality falls short. Poor road conditions, limited connectivity, and high transportation costs hinder the efficient and timely distribution of inputs.

Poorly maintained roads can disrupt input delivery during the wet season in remote areas like Wukari. Farmers already struggle to acquire the necessary inputs, and a lack of direct road links exacerbates the issue, leading to higher input costs and delivery delays. This situation results in lower yields and increased post-harvest losses, adversely affecting farmers' livelihoods and household well-being [9].

Inefficiencies in input distribution can also have broader economic impacts. A drop in agricultural production would hurt the local economy in Wukari, reducing job opportunities and income. Poor national road infrastructure may decrease agricultural output, slowing overall economic growth. Despite these significant challenges, there is a lack of research on the complex interplay between road transport factors and the distribution of inputs in Wukari. To fill this knowledge gap, researchers must investigate how road factors affect the allocation of agricultural inputs in the Wukari community.

HYPOTHESIS

Null Hypothesis (H0): The distribution of agricultural inputs is significantly affected by factors related to road transport in Wukari, Taraba State, Nigeria.

2. Literature Review

2.1. Theoretical Framework

Applying transportation cost theory (TCT) can improve understanding of agricultural input distribution in regions like Wukari in Taraba State, Nigeria. Agriculture is vital to rural economies and daily life, which renders coordinating transportation networks, costs, and logistics essential for efficiently distributing inputs. To determine TCT's effectiveness in this context, we need to examine factors influencing road transport, focusing on affordability, accessibility, and reliability of input delivery to rural farming communities.

Transportation cost theory (TCT) emphasizes the importance of transportation costs in shaping economic activity and resource allocation. In Wukari, factors such as road conditions, distance to markets, and the availability of transport services greatly affect transportation expenses, as road transport is the primary method for delivering farm inputs. Poor road infrastructure, impassable routes during certain seasons, and limited transportation alternatives can all hinder efficient input distribution, impacting agricultural productivity and rural development.

The application of TCT principles to road transport variables shows the theory's relevance to input distribution. Studies by reference [15] & [2] highlight the supply chain management challenges posed by geographical differences in agricultural transportation costs in Nigeria. These findings underscore the importance of considering regulatory factors, market accessibility, road conditions, and other transport characteristics when examining agricultural input distribution. Looking at empirical evidence from similar regions facing comparable transportation challenges can offer insights into optimizing input distribution networks. For instance, reference [6] study on Sweden's industrial distribution illustrates how improved logistics management and transportation infrastructure can reduce costs and enhance market access for rural businesses.

Applying TCT to agricultural input distribution also has significant policy implications. Stakeholders and policymakers can use TCT findings to enhance system efficiency, reduce transportation costs, and improve road infrastructure. Investments in road maintenance, alternative transportation modes, and supportive policies can boost rural development and economic growth in agricultural areas such as Wukari, strengthening the agricultural supply chain.

The transportation cost theory (TCT) clearly explains how the distribution of agricultural inputs works in Wukari, Taraba State, Nigeria. It does this by showing how road transport variables, transportation costs, and distribution dynamics all interact in complex ways. Researchers and policymakers can use TCT concepts to enhance the efficiency and sustainability of rural agricultural systems, addressing the potential and challenges of input allocation. In Wukari, the transportation infrastructure relies heavily on road transit to move people, goods, and services over long distances.

Factors such as road quality, connectivity of road networks, availability of transportation hubs, transport infrastructure, and regular road maintenance significantly affect the effectiveness and efficiency of road transport. Each element plays a crucial role in determining the region's road accessibility, safety, and reliability.

2.2. Conceptual

ROAD QUALITY

In terms of the road's physical condition, which includes aspects like pavement condition, smoothness, and durability, we talk about road quality. There is a wide range in road quality in certain routes deteriorating owing to a lack of maintenance and severe weather. Congestion, higher transportation expenses, and driver safety issues can all result from roads that aren't up to par. On the flip side, roads that are well-kept make travel easier, last longer between repairs, and boost the economy. Road quality heavily influences transportation costs and supply chain management, as demonstrated by [2].

CONNECTED ROAD NETWORKS

We refer to the density and breadth of the road network connecting to its surrounding towns, cities, and regions as a connected road network. A well-connected road network leads to better accessibility and easier movement of people and commodities are the results of a well-connected road network. Not all regions have the same level of road network connectivity; in fact, some places may be quite isolated from important arteries of travel. Building more roads, bridges, and bypasses can improve connectivity, which in turn can shorten travel times, increase trade, and boost the economy. Reference [13] found that the connectedness of road networks in Nigeria affects the spatial variation in transportation costs for agricultural products.

TRANSPORTATION HUBS

Transportation hubs are important nodes that allow people and goods to move in and around. Transportation terminals, truck stops, and freight depots are examples of hubs that facilitate cargo consolidation, transfer, and dispatch to other locations. Properly equipped transportation hubs are crucial for improving logistical efficiency, reducing congestion, and enhancing coordination among different modes of transportation. When transportation hubs lack adequate infrastructure and facilities, they can hinder the smooth movement of goods and people. Therefore, to optimize the efficiency of road transport networks, it is vital to invest in and effectively manage these hubs [4].

ROAD TRANSPORT INFRASTRUCTURE

Road transport infrastructure encompasses a variety of components, such as roads, bridges, tunnels, toll booths, and signs. The network depends on these elements to ensure mobility and connectivity. Investments in road transport infrastructure are vital for reducing travel times, enhancing safety, and handling increased traffic. Improving road infrastructure can lead to better access to markets, employment opportunities, and social services, thereby fostering economic growth. According to reference [19] investing in road transport infrastructure is essential for promoting equitable growth and reducing poverty in developing countries.

REGULAR MAINTENANCE OF ROADS

Keeping roads well-maintained is essential for ensuring their quality, safety, and longevity. Maintenance tasks include patching potholes, repaving damaged sections, clearing vegetation, and repairing drainage systems. Routine maintenance is vital to prevent road deterioration, reduce vehicle running costs, and avoid disruptions in transportation services. Therefore, preventive maintenance is key to keeping the road network functional and efficient.

According to reference [5] regular road maintenance enhances transportation system performance and supports sustainable development. Several factors influence road transport, such as road conditions, the number of connections between roads and transportation centres, the infrastructure supporting road transport, and the frequency of maintenance. To improve the region's road transportation accessibility, safety, and reliability and thus foster economic growth and development it's important to address these factors through targeted investments, legislative actions, and effective management practices.

2.3. Empirical Review

Reference [4] conducted a literature review and analysis to determine the effect of transportation variables on agricultural development in Nigeria. According to the research, the country's poor road infrastructure, high transportation costs, and insufficient transportation services are the main obstacles to the distribution of agricultural inputs. Reference [4] proposed enhancing road infrastructure, controlling transportation services, and subsidizing farmers' transportation expenses as solutions to these problems.

Reference [9] conducted a literature study and analysis to explore the opportunities and threats associated with managing road traffic for agricultural growth in Nigeria. Research reveals that factors like road quality, transportation costs, and regulatory frameworks influence the distribution of agricultural inputs across the nation. Building roads, managing transportation efficiently, and creating laws to help farmers succeed were all things the authors said would boost agricultural growth.

Reference [12] investigated the causes and effects of insufficient farm inputs on small-scale cocoyam producers in Cross River State, Nigeria, using survey data analysis. The study revealed that factors such as poor road infrastructure, high transportation costs, and limited access to farm inputs significantly impact small-scale farmers' production. The researchers suggested that small-scale farmers could benefit from subsidies for agricultural inputs, better road infrastructure, and easier access to financial facilities. Through a literature study and analysis, [10] addressed the function of transportation in Nigerian agriculture and its effects on the distribution of farm inputs. The research demonstrated the influence of transportation costs, road infrastructure, and regulatory frameworks on the distribution of agricultural inputs. To encourage agricultural development in Nigeria, the authors proposed investment in transportation infrastructure, efficient transportation service promotion, and effective regulatory policies as means to encourage agricultural development in Nigeria.

Reference [14] examine the relationship between the efficiency of agricultural input distribution and the quality of the roads leading to those regions. Various emerging nations have varying geographical and economic situations. We used a mixed-methods strategy, combining quantitative surveys and qualitative interviews, to gather detailed data from a sample of 1,000 rural families across these regions. The results show that there is a direct correlation between better road infrastructure and higher agricultural productivity. This is because better roads allow access to markets, which in turn reduces transportation costs and time. Furthermore, when roads are of excellent quality, they can distribute agricultural supplies like seeds, fertilizer, and equipment more efficiently. This allows for more precise scheduling of planting and harvesting. Research shows that improved road infrastructure boosts rural economies by reducing transportation costs and post-harvest losses, which in turn increases farmers' income and encourages further investment in rural areas. To make the most of better road infrastructure in emerging areas, the authors suggest combining agricultural policy with targeted expenditures on road building and maintenance [14].

Reference [15] investigate the impact of road networks on agricultural productivity in different regions. Eight hundred smallholder farmers from three different regions participated in the cross-sectional survey that formed the basis of the research. By lowering transportation costs and improving access to markets and agricultural inputs, their research shows that better road infrastructure greatly increases agricultural productivity [15].

Reference [16] investigates the correlation between improved road networks and increased crop yields in Ethiopia. The study shows that better roads lead to better input delivery and higher agricultural output. It used a mixed-methods approach and surveyed 500 farming households. According to the study, infrastructure plays a key role in helping Ethiopia's economy and agriculture thrive [16].

3. Methodology

The study employed descriptive survey research design. The paper adopted a quantitative survey design in order to obtain quick, efficient, and accurate information about a representation of a population. This study fits into a survey method design because it seeks to assess the impact of road transport determinants on distribution of farm inputs in Wukari, Taraba State, Nigeria, given the nature of the research problem and the need to make meaning from the data generated from the population sample in an efficient manner. The population of this study includes all potential farmers in the study areas. The study adopted a convenient sampling technique to select the sample size of 200 respondents.

The primary source of data was the self-designed research instruments that were administered to the respondents in the sample. For the study instrument, content and construct validity were used, and Cronbach's alpha was used to measure the study instrument's reliability. Data analysis makes use of descriptive inferential statistics. Inferential statistics based on simple regression analysis were used to test the hypothesis formulated.

Simple regressions

$$Y_{2_t} = \aleph + \varphi F_{1_t} + \beth F_{2_t} + \infty F_{3_t} + \beta F_{4_t} + \gamma F_{5_t} + \mu_t$$

Where:

Y_2 is the dependent variable

F_{1-5_t} is set of latent factor composition (explanatory variables);

φ, $\beth$, ∞, β and γ are parameter estimates of the model that explains independently how each explanatory variable predicts variations in the dependent variable.

$\aleph$ is the value of the dependent variable when all explanatory variables are zero.

Independent Variables (F_{1-5_t})

Dependent Variable (Y_{2t})

The dependent variable for the study was distribution of farm inputs while road transport determinants were independent variable used in regression analysis.

Table 1. Model Summary on the Impact of Road Transport Determinants on Farm Input Distribution in Wukari, Taraba State, Nigeria

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
1	0.191[a]	0.036	0.032	3.36751	1.095

a. Predictors: (Constant), Transport Determinants

b. Dependent Variable: Impute Distribution

Table 1 provides a summary of the regression model utilized to assess the impact of road transport determinants on farm input distribution. The model exhibits a coefficient of determination (R Square) of 0.036, indicating that approximately 3.6% of the variance in farm input distribution is explained by the transport determinants under study. The adjusted R Square, which accounts for the number of predictors in the model, is slightly lower at 0.032, suggesting a minimal but noticeable influence of these determinants on the distribution process. The standard error of the estimate is 3.36751, reflecting the average distance that the observed values deviate from the line of best fit. Additionally, the Durbin-Watson statistic of 1.095 indicates potential positive autocorrelation in the residuals of the regression model, suggesting that the data points may not be entirely independent.

Table 2. ANOVA on the Impact of Road Transport Determinants on Farm Input Distribution in Wukari, Taraba State, Nigeria

Model	Sum of Squares	Df	Mean Square	F	Sig.
Regression	85.032	1	85.032	7.498	0.007[b]
Residual	2245.348	198	11.340		
Total	2330.380	199			

a. Dependent Variable: Impute Distribution

b. Predictors: (Constant), Transport Determinants

The Analysis of Variance (ANOVA) detailed in Table 2 supports the regression model by providing insight into the overall significance of the model. The regression sums of squares (85.032) with a degree of freedom of 1 indicates the variation explained by the model. The residual sum of squares (2245.348) with 198 degrees of freedom represents the unexplained variation. The F-statistic of 7.498 at a significant level of 0.007 decisively suggests that the model is statistically significant, indicating that the road transport determinants significantly influence the distribution of farm inputs, albeit modestly.

Table 3. Coefficients on the Impact of Road Transport Determinants on Farm Input Distribution in Wukari, Taraba State, Nigeria

Model	Unstandard. Coeff.		Standard. Coeff.	T	Sig.	95.0% Conf. Interval for B		Collinearity Statistics	
	B	Std. Error	Beta			Lower Bound	Upper Bound	Tolerance	VIF
Constant	12.584	1.123		11.202	0.000	10.368	14.799		
Transport Determinants	0.193	0.071	0.191	2.738	0.007	0.054	0.333	1.000	1.000

Table 3 provides detailed insights into the influence of individual predictors within the model. The constant term (12.584), significant at the 0.05 level, implies a baseline value for the farm input distribution when all predictors are held at zero. The coefficient for transport determinants (0.193) with a standard error of 0.071 and a standardized coefficient (Beta) of 0.191 suggests that as the transport determinants improve by one standard unit, farm input distribution increases by approximately 0.193 units, holding other variables constant.

This relationship is statistically significant at the 0.007 level. The confidence interval for this coefficient (0.054 to 0.333) suggests a positive influence of transport determinants on farm input distribution with 95% confidence. The collinearity statistics, with a tolerance of 1.000 and a variance inflation factor (VIF) of 1.000, indicate no collinearity issues, affirming the model's reliability.

4. Discussion Of Findings

Results from a regression study on the factors influencing the distribution of agricultural inputs in Wukari, Taraba State, Nigeria, found that road transport was a key contributor. At the 0.05 level of significance, the data reveals a constant-term baseline value of 12,584 for farm input distribution. This suggests that a standard distribution of farm inputs already exists, even without any changes to the predictors. Also, the transport determinants a coefficient of 0.193 with a standard error of 0.071 are statistically significant at the 0.007 level, with a 95% confidence interval spanning from 0.054 to 0.333. This is an important finding. It means that for everyone standard unit improvement in transport determinants, there is an increase of about 0.193 units in the distribution of farm inputs. The beta coefficient of 0.191 further supports this relationship.

These results underline the significance of upgrading transportation infrastructure to better distribute agricultural inputs. Our study's outcomes align with previous research on the impact of transportation on agricultural productivity, especially in Nigeria. They confirm the critical role that poor road infrastructure, high transportation costs, and inadequate services play in the distribution of agricultural inputs, similar to the issues observed by [4] and the proposed solutions. Our findings are consistent with studies by [9], which highlight the influence of road infrastructure and regulatory frameworks on agricultural development.

The empirical evidence we gathered supports the study's recommendations for infrastructure and management improvements, proving that these interventions are beneficial. Additionally, reference [12] examined how transportation affects small-scale farmers in Nigeria, demonstrating that enhancing transportation infrastructure can increase agricultural productivity at all levels. All of these studies add up to back up our regression analysis, which shows that transport factors have a major impact; therefore, we should make strategic transportation enhancements to help the region's agricultural development. There are a number of parallels and dissimilarities between the study's findings on the effect of road transport factors on the distribution of farm inputs in Wukari, Nigeria, and the publications' conclusions on the relationship between Africa's road infrastructure and agricultural output.

All of the research points to the same conclusion: better road infrastructure increases the distribution and productivity of agricultural inputs. To illustrate this point, the study's coefficient (0.193, SE = 0.071, Beta = 0.191) shows a positive and statistically significant association between transportation determinants and the distribution of farm inputs. This suggests that when transportation conditions improve, farm input distribution also increases. This result is in line with the larger body of research showing that increased agricultural output is a direct result of better roads, which decrease transportation expenses and increase accessibility to inputs and markets [15] & [16]. Just as the strong collinearity statistics in this study confirm the model's reliability, they also guarantee the validity of the found link. While this study specifically focuses on Wukari, Nigeria, and its unique socioeconomic and infrastructural factors.

Also, this study uses specific statistical measurements like confidence intervals and standardized coefficients for its quantitative methods. Other studies may use mixed-method approaches or different statistical techniques, which can change the breadth and depth of their findings. Despite these differences, there is a consensus among researchers about the crucial role of roads in agricultural development, emphasizing the need for targeted infrastructure investments to enhance agricultural productivity in various contexts, as noted [1].

5. Contribution to Knowledge

This research significantly contributes to the fields of agricultural economics and rural development. It investigates how various factors affecting road transport influence the distribution of agricultural inputs in Wukari, Taraba State, Nigeria. By focusing on a local context, the study broadens our understanding of how transportation infrastructure impacts agricultural supply chains. The study provides thorough statistical analysis that clearly demonstrates the relationship between better transportation and the more extensive distribution of agricultural supplies.

Policymakers and planners can use the findings' quantifiable evidence to enhance agricultural productivity through infrastructure development. Specifically, they show that a one-standard-unit improvement in transport determinants leads to a 0.193 increase in farm input distribution. This particular metric provides a more detailed understanding of transport economics in agricultural contexts, paving the way for more precise actions. Wukari is a major agricultural hub in Taraba State, and this study fills a knowledge vacuum in area statistics by examining the monetary effects of transportation on the agricultural sector there. Up until now, we have only partially understood the logistic dynamics impacting agricultural input supply in this region, primarily relying on anecdotal evidence and larger national studies that may have overlooked regional differences.

This study's regional emphasis allows for the collection of nuanced information that might inform development and policy initiatives tailored to the unique circumstances in Wukari. Additionally, by confirming that transit determinants, not confounding factors, cause the observed effects, the analysis's incorporation of collinearity diagnostics guarantees the results' credibility. The results are more convincing, and the study's conclusions are based on solid statistical evidence because of the rigorous methodology used.

However, by aligning its findings with existing literature that discusses the broader impacts of road infrastructure on agricultural development, this research not only corroborates previous studies but also adds a critical empirical foundation to theoretical discussions. It reinforces the argument that improving transport infrastructure is essential for facilitating access to farm inputs, thus directly contributing to agricultural productivity and rural economic growth.

This study makes a valuable academic contribution by providing concrete evidence and specific data points that highlight the critical role of transportation in agricultural logistics. It provides a solid foundation for future studies and policymaking in related fields by arguing persuasively for the strategic improvement of transportation networks to increase agricultural production.

6. Recommendations for Future Research

The findings from this study on how road transport factors affect the distribution of farm inputs in Wukari, Taraba State, Nigeria, suggest several areas for further investigation. To expand and deepen our understanding, we recommend the following research directions:

1. Comparative Studies Across Regions: Future research could compare different regions within Nigeria or even other countries with similar agricultural conditions. This would help us understand how variations in transportation networks impact the distribution of agricultural inputs and reveal which local factors might influence the effectiveness of transportation infrastructure improvements.

2. Long-Term Observational Studies: Conducting studies that track how agricultural input distribution evolves over time in response to transportation improvements would provide valuable insights. This could highlight both the long-term benefits and any unintended consequences of investing in transportation infrastructure.

3. Incorporating Additional Variables: To get a fuller picture of what influences the distribution of farm inputs, future studies should consider other factors such as economic policies, changes in market demand, and the quality of farm inputs. This approach would help us understand both the direct and indirect effects of transportation on agricultural production.

4. Advanced Statistical Techniques: Employing advanced statistical methods, such as structural equation modelling or multi-level hierarchical models, could offer a more detailed understanding of how transportation factors interact with other elements of agricultural supply chains. These suggestions aim to build on the current study's findings and explore new avenues for improving agricultural input distribution.

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LDPC Codes for 5G: An Empirical Analysis for Wireless Communication System Advances

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Abstract With advancements and new proposals in wireless communication standards, there is an increase in the demand for band-width-efficient wireless transmission mechanisms. The 5G networks will also enable the Internet of Things (IoT) by creating more efficient and reliable networks for billions of connected devices. Error-Correction Coding (ECC) is a powerful technique to ensure reliable and secure communication in wireless multimedia systems. ECCs are essential for modern wireless communication as they help reduce the amount of data lost during transmission due to errors and noise in the channel. Recent research has demonstrated the usefulness of Low-Density Parity-Check (LDPC) codes for 5G and beyond communication. This paper compares LDPC with polar, Reed-Muller, and convolutional codes, along with a motivation for their application in wireless multimedia communication. Simulation results show that the LDPC outperforms Reed-Muller, polar, and convolutional codes for larger block length codes. Thus, two sub-classes of LDPC codes, AR4JA and AR3A, with different decoding algorithms, are presented for possible adoption in next-generation reliable communication. The performance is evaluated in terms of the Bit Error Rate (BER) and code rate. The paper also highlights the importance of using ECCs in wireless multimedia communication to improve data transmission reliability and reduce channel impairments' impact. More specifically, the AR4JA exceeds the AR3A by a factor of 0.5 dB SNR at the BER degradation point of 10-8 and attains the error floor level of 10-9.

Keywords 5G LDPC, Error-Correction Coding (ECC), the Bit Error Rate (BER)

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1. Introduction

Wireless technology has grown exponentially over the last few decades [1]. The recent advancement in wireless technology has boosted the potential capabilities of the Internet of Things (IOT), increased data capacity by 30–40% , and resulted in high bit rate transmission [2]. Researchers have significantly developed in resolving constraints related to low bandwidth, high-data-rate transmission, and service cost [3].

Although wireless communication networks provide high-speed data transmission, low-cost maintenance, and ease of installation [4]. However, the rising demand for high-data-rate transmission in wireless technology has brought new challenges to communication systems. These challenges are security and Privacy, portability [5], communication infrastructure [6], mobility, coding, limited bandwidth, and wireless access techniques [7].

In wireless communication, the transmission of multimedia contents is supported by source and channel coding techniques [8]. For efficient multimedia data compression, source encoding has received much attention [9, 10]. Error-correction coding is a technique used to describe a series of numbers in a form that allows errors to be found and fixed, subject to constraints imposed on the remaining numbers. The main focus of channel coding is to reduce the effect of errors in a communication link and the system's complexity, allowing for practical implementation. Massive machine-type communications (mMTC), enhanced mobile broadband, and ultra-reliable and low latency communications (URLLC) (eMBB) are three scenarios supported by the next-generation communication network, 5G NR, beyond 4G LTE [11-13]

These scenarios require reliability, low latency, less computational cost, and improved throughput compared to 4G LTE [14]. Considering these requirements, low-density parity check (LDPC) codes were implemented for the 5G standard for data channels [15, 16]. During the 5G standardization study phase, several coding schemes were tested based on the mentioned requirements and adopted polar coding for eMBB scenario control information and LDPC coding for user data.

Following are some of the significant contributions of this treatise:

- Comparison of LDPC codes with different FEC for performance estimation.
- Effect of variation in the block length of LDPC codes on error-resiliency.
- Investigation of the types of LDPC for deployment in 5G communication setupTop of Form.

In Section II, we describe some of the related work in modern wireless communication. Sections III, IV, V, and VI discuss basic LDPC coding, Polar codes, advanced 5G LDPC coding, and 5G polar coding. Section VII covers Reed-Muller codes, while Section VIII elaborates on convolutional codes. Experimental results are given in Section IX. Finally, Section X briefly concludes the article along with future research directions.

2. Related Work

Gallager developed LDPC codes during his Ph.D. studies, and it was established that the results of communication systems could approach the Shannon capacity when LDPC codes are used for channel encoding [19]. Soft-in and soft-out information is utilized for LDPC codes to enhance diversity and reduce complexity. Multiple nodes transmit the code-words along a shared path. Due to the random nature of LDPC codes, there is no need for an interleaved [19]. Using LDPC codes allows for exchanging external and internal information, facilitating cooperation and suggesting that cooperative decoding is superior to other methods. A study [20] combines JSCC and LDPC for increased effectiveness. Iterative decoding requires Tanner-graph mapping of the source and channel coding using a message-based approach. In [21], the authors propose using superposition-coded modulation for wireless channel video transmission. LDPC codes are employed for encoding videos, resulting in higher-quality videos. The authors suggest reducing complexity through repeated decoding, achieving a 67% decoding success rate. The concept of using path sharing to create a multicast system while utilizing the same media is presented in [22]. Polar codes, invented by Turkish scientist Arikan [23], are error correction codes used in communication systems. They serve as a reliable channel encoding scheme and are employed as coding schemes in fifth-generation networks for error correction [24].

3. LDPC Codes

LDPC codes are a valuable class of error-correction codes for efficiently improving the above parameters. LDPC provides practical implementation near Shannon channel capacity and greater speed and accuracy with less complex algorithms. LPDC codes are specified by a parity check matrix containing a few ones and primarily zeros. LDPC codes can be represented in two ways: in matrix form and graphical representation. In LDPC codes, the sparse parity check matrix ((n-k) × n dimension) represents the parity check sets. Sparse means that the condition (w_c and w_r << n×(n-k) should be satisfied, where n represents the coded length, w_r, and w_c represent the number of ones in a row and column, respectively [19].

A sparse parity check matrix of (n = 8, w_c = 4, w_c = 2) is presented in equation 1, where each row appears to be a check node and each column is a variable node [19].

$$H=\begin{bmatrix} 0 & 1 & 0 & 1 & 1 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 & 1 & 1 \\ 1 & 0 & 0 & 1 & 1 & 0 & 0 & 1 \\ 1 & 1 & 1 & 0 & 0 & 1 & 0 & 0 \end{bmatrix} \quad (1)$$

The 1's in the H matrix represent the connection between the variable node and the check node. The parity check matrix can be categorized into two types. The codeword of any linear block code associated with LDPC codes, including message and parity bits, can be described in Equation 2.

$$C = [m_{1\times k} \quad P_{1\times n-k}] \quad (2)$$

Where p represents the parity vector and m represents the message vector. Figure 1 shows the 5G LDPC codes encoding procedure [19].

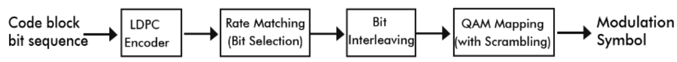

Figure 1. Encoding process timof 5G LDPC codes.

4. Polar Codes

Polar codes were initially presented in 2009 by Erdal Arıkan [17]. The first linear code achieved the Shannon channel capacity. Polar codes have an excellent structure with efficient and less complex encoding and decoding operations. The LDPC relies on ensemble performance levels, whereas the polar codes can be confirmed using a specific realization. Identifying frozen bit positions and information is another crucial aspect of polar codes [18-20].

Although the achievable polar code capacity with SC decoding is impressive, its finite length capacity, compared to other channel coding, is even worse. List decoding is a well-known solution for this matter [21]. Successive cancellation list (SCL) decoding keeps multiple decision candidates during successive cancellation (SC) decoding to overcome the premature decision drawback of SC decoding. Moreover, CRC-aided (CA) SCL is considered for error detection and correction to enhance the block-error rate (BLER) performance of SCL decoding. Furthermore, several solutions were presented in previous literature to overcome the latency issue of SC decoding [22-24]. The 5G polar transmitting processing chain is present-ed in Figure 2.

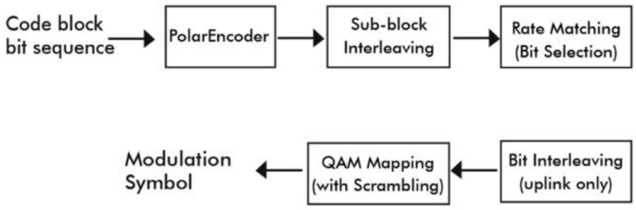

Figure 2. 5G polar codes transmitter processing chain

5. 5G LDPC Codes

The main features of 5G LDPC codes are briefly described in this section. QC-LDPC codes are 5G LDPC codes related to the protograph code family. This section explains the design of a permutation matrix and a photograph, two crucial components of the protograph code. Moreover, rate matching procedures and IR-HARQ support, are also described.

5.1. Protograph codes

The fifth-generation LDPC codes are QC-LDPC codes [25]. The concept of protograph codes will help explain QC-LDPC codes. The graphic representation of protograph codes can be obtained by affixing numerous protograph copies and rearranging the borders between them. The check nodes and variables are initially identified from each protograph copy in the edge permutation process. The local connection between check nodes and variables is vital for better performance. It is important to design a better permutation pattern with efficient cycle properties for better performance of protograph codes. Several observations have been presented in the literature showing the better finite-length performance of protograph codes in various environments [25].

Table 1: Shift-value sets and lifting sizes set for 5G LDPC codes with their relation.

Index of Shif-value set	Lifting sizes (Z) set							
0	2	4	8	16	32	64	128	256
1	3	6	12	24	48	96	192	389
2	5	10	20	40	80	160	320	
3	7	14	28	56	112	224		
4	9	18	36	72	144	288		
5	11	22	44	88	176	352		
6	13	26	52	104	208			
7	15	30	60	120	240			

Moreover, protograph codes allow parallelism in the encoding and decoding processes [26], which is advantageous in the case of layered decoding [27]. In the 5G specification [28], a photograph is formally known as a base graph. The base graph has two types whose usage is determined by the size of the code rate or information bit. The parity check matrix can be constructed through the base graph by replacing the nonzero entries with a Z × Z permutation matrix and the zero entries with a Z × Z zero matrix. During each cycle of decoding the layer, each check/variable node is evaluated sequentially.

Contrarily, the flooding schedule updates messages for all check nodes concurrently (in parallel) during the first half of the decoding process and the opposite for all variable nodes simultaneously during the second half. Although it is not parallelized as a flooding schedule, layered decoding often speeds up convergence in terms of iterations of decoding. The like nodes from each protograph copy can be processed simultaneously without affecting the layered decoding performance. Such types of parallelism have a critical effect on high throughput. In addition, the identity matrix of the QC-LDPC code permutation is circularly shifted. A single number can represent each permutation when a permutation matrix with a circularly shifted identity matrix is used. This will make employing a straightforward switch network easier for the encoding and decoding process and decrease the amount of RAM needed to implement it [29]. About 51 lifting sizes (Z) are included in the 5G specification, with eight permutation matrices per base graph. These lifting sizes and permutation matrix designs are presented in Table 1.

5.2. Base graph Design

To ensure that LDPC codes function better, base graph design is similarly as essential as shift values. The base graph regulates the improved local connection between check nodes and variables. We need to discuss the LDPC codes' capacity and achievability before going into the detail of the base graph design of 5G LDPC codes. However, these codes promised to improve the capacity of MBIOS channels. The variable ($\lambda(x)$) degree distribution and check nodes ($\rho(x)$) are shown in Equation 4 and Equation 5, respectively.

$$\lambda(x) = \sum_i \lambda_i \times x^{i-1} \quad (4)$$

$$\rho(x) = \sum_i \rho_i \times x^{i-1} \quad (5)$$

The edges' fraction linked to the variable or check node is represented by $\lambda_i(\rho_i)$ with i degrees. The $\lambda(x)$ and $\rho(x)$ defined the standard ensemble as the LDPC code ensemble. If they contain a single term, it is referred to as regular and it is referred to as irregular otherwise. Unfortunately, a traditional ensemble cannot attain the MBIOS channel capacity until the parity check matrix density increases to infinity compared to code length. However, such an unfavorable finding does not always true when the standard ensemble is modified. By inserting punctured variable nodes or various edge types, such as the proportion of accumulator in IRA codes [30], several LDPC codes [31, 32] are proposed to provide MBIOS channel capacity with finite density.

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5.3. Quasi-cyclic Low-density Parity-check (QC-LDPC) codes

QC-LDPC codes are the enhanced standard 5G codes for mobile broadband data channels [33]. These codes support rate-compatible properties [34] and multiple lifting sizes and have adapted well to the various code rates and information lengths. QC LDPC codes. These codes are investigated extensively and are used in numerous applications in storage systems and digital communications [35-37] because of their simple hardware implementation, lower error floor, and fast decoding convergence. The channel coding strategy for 5G eMBB data channel communication is considered QC-LDPC codes [38].

5.4. AR3A and AR4JA Codes

Abbasfar introduced the Accumulate Repeat and Accumulate (ARA) codes, a subclass of LDPC codes [39, 40]. These codes were proposed because of their simple encoder substructures and efficient decoding performance. AR3A codes use repetition-3 and are suitable for LDPC structures. From the AR3A protograph, it can be seen that the variable nodes of degree 1 are introduced by means of an inner accumulator. AR4JA codes are ARA codes with repetition 4 in them. AR4JA codes should achieve better error floor performance and a higher minimum distance. The experimental section will present a comparison of performance between regular LDPC codes, AR3A codes, and AR4JA codes.

6. 5G Polar Codes

A polar code (represented by (N, K)) has K (NR) no of inputs and N number of outputs with code rate R. An encoder of length N will be used for encoding the 5G polar codes, While the remaining inputs (N-K) Consider a polar code (represent-ed by (N, K)) with K (NR) inputs and N outputs and a code rate of R. An encoder of length N will be used for encoding the 5G polar codes. In contrast, the remaining inputs (N–K) are held constant (frozen). By selecting A for any subset of k, where k = 1, 2,..., N, a polar code (N, K) can be generated. However, to get an efficient code, we must choose A carefully. In order to select option A, all GN inputs without frozen bits will be imagined, and the probability of a decoding error will be determined for each input. The input set with the lowest error probability, A, will be selected as the input set for optimizing the polar code for W. 5G polar codes can have code lengths of 2n for $5 \leq n \leq 10$ for uplink. While $7 \leq n \leq 9$ for downlink. For the uplink, 5G polar codes can have code lengths of 2n for $5 \leq n \leq 10$, while $7 \leq n \leq 9$ is often used for downlink. We have attained the MBIOS channel capacity using SC decoding polar codes [41]. For decoding polar codes, use the Successive Cancellation (SC) decoder. For each encoder, the input bit u_i with polar codes [41].

7. Reed-Muller Codes

The Reed-Muller (RM) codes were initially introduced in 1956 by Muller [42] and are mainly used in deep-space commu-nication. Assume G represents the nth order generator matrix for RM codes with N = 2n blocks as shown in equation 8.

$$G(n, n) = F \oplus n \tag{8}$$

where,

$$F = \begin{vmatrix} 1 & 0 \\ 1 & 1 \end{vmatrix} \tag{9}$$

Where $F \oplus n$ represents the nth tensor power of F, as shown in equation 9. The RM code (r^{th} order) can be obtained as a linear code with the generator matrix G(r,n) [51,52]. The G(r,n) matrix can be calculated by taking the rows of G(n,n) and $2^{n-r} \leq$ Hamming weights, as shown in equation 10.

$$G(3,3) = \begin{vmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 1 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{vmatrix} \tag{10}$$

While RM (1,3) is a reed muller code with the generator matrix G(1,3) as shown in equation 11.

$$G(1,3) = \begin{bmatrix} 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 1 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix} \tag{11}$$

RM decoders are categorized into two parts: non-iterative and iterative decoders. The Dumer recursive list decoding algorithm [43], known as SCL decoding, is the most well-known RM decoder for an additive white Gaussian noise channel. Recently, a new decoding algorithm, Recursive Projection Aggregation (RPA) decoding, was proposed in [44].

8. Convolutional Codes

Convolutional codes are error-correction code in which output bits are determined by performing a logical operation on the present bitstream with the previous bits. This code uses A shift register to temporarily store the bits with shifting operations and an XOR logic circuit. The two main parameters of convolutional coding are constraint length and code rate. The constraint length is the window size (in bits) inside the shift register or the encoder's length. However, equation 12 gives the code rate (r_c) while code rate is the proportion of bits in the encoded bitstream to bits shifted all at once in the shift register (k)/(n).

$$r_c = \frac{k}{n} \tag{12}$$

In a convolutional encoder, there are two states, x[n-1] and x[n-2], and the input bit x[n]. The encoder bits X_1 and X_2 are obtained from an XOR operation and shown in Equation 13 and Equation 14.

$$X_1 = x[n] \oplus x[n-1] \oplus x[n-2] \quad (13)$$

$$X_2 = x[n] \oplus x[n-2] \quad (14)$$

Convolution codes are a coding error technique commonly used in communication systems. It encodes certain replicated data into messages and enhances the efficiency of the network's data. Furthermore, it is a fast-coding technique with good results and limited integration costs [55]. However, this technique is computationally intensive and fails to fix explosion errors without interleaving. The complexity and performance of convolutional codes were compared in the literature [45-47]. However, literature [48, 49] investigated convolutional code applications.

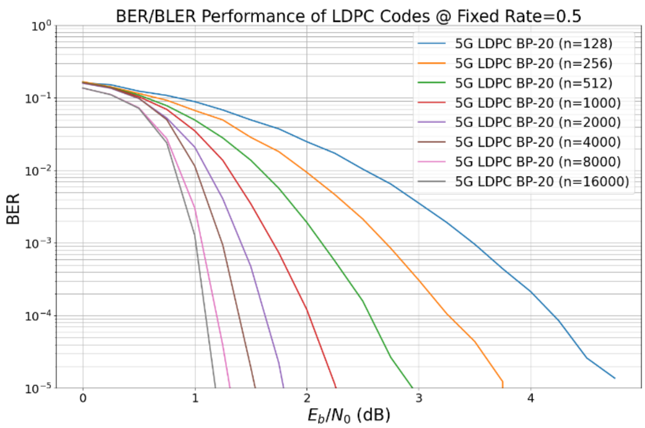

Figure 3. BER/BELR Performance of LDPC codes @ Fixed Rate = 0.5.

9. Experimental Results

This section offers a comparative study of these codes to highlight the justifications for choosing LDPC, polar, Reed-Muller, and/or convolutional codes. The BER performance for a fixed half-rate LDPC code with a varying number (n) of inputs is presented in Figure 3. It is plausible that the larger the number of input bits to the LDPC encoder, the better the performance of that variant in terms of BER. Figure 4 gives the performance of the bit error rate of LDPC codes on an AWGN channel with a fixed rate of 0.5 for different code length values (n).

Figure 5 presents an EXIT chart analysis of LDPC codes. It is viable that the EXIT curves meet after a few iterations at the point of convergence, showing that the LDPC codes can attain an infinitesimal BER. Figure 6 compares the BER curves of LDPC with those of polar SC and SCL-8+CRC, Reed-Muller, and convolutional codes. The evaluation is performed regarding BER vs. SNR for larger block codes. The simulation results show that 5G LDPC codes provide better BER than polar, Reed-Muller, and convolutional codes.

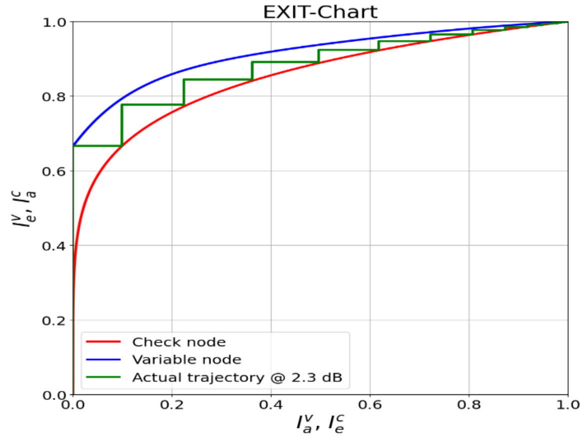

Figure 4. EXIT Chart Analysis of LDPC Codes

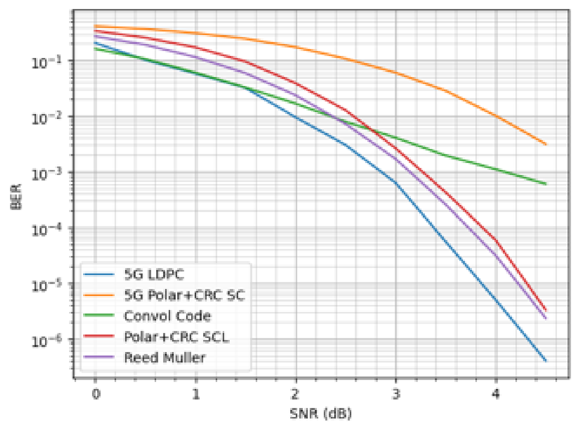

Figure 5. BER/BLER Performance of Larger Length Codes.

The result shows that the AR4JA for different decoding algorithms provided better performance and attained the error floor as compared to AR3A. Figure 7 presents the performance of Regular LDPC, AR3A, and AR4JA codes with family rates of 1/2 and 2/3 over the AWGN channel. It can be seen that the AR4JA sub-class outperforms the AR3A and regular LDPC codes for both 1/2 and 2/3 overall code rates.

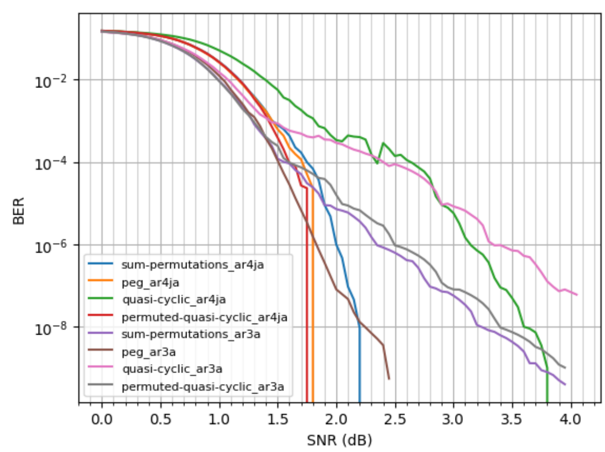

Figure 6. Comparison of Performance of PEG AR3A, PEG AR4JA, Quasi cyclic AR3A, Quasi cyclic AR4JA, Permuted quasi-cyclic AR3A, and Permuted quasi-cyclic AR4JA.

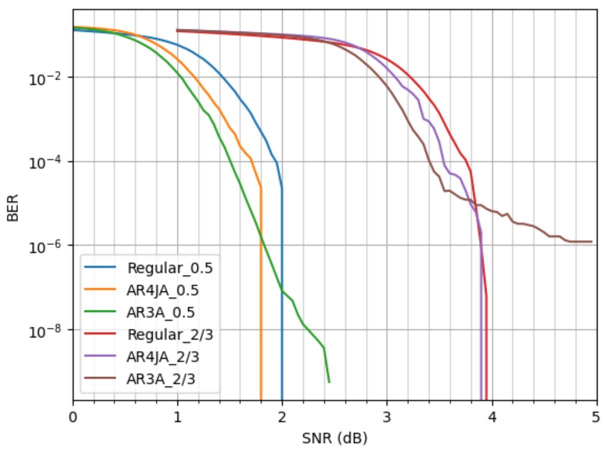

Figure 7. Performance of Regular LDPC, AR3A, and AR4JA codes family over AWGN channel.

9. Conclusion

The results of this paper shed light on the trade-offs between different codes for 5G wireless communication, aiming to enhance the speed, capacity, and reliability of wireless networks and enable a higher number of devices to connect to the internet. The paper evaluates the performance of 5G LDPC codes and compares them with various error-correction coding schemes such as convolutional, Reed-Muller, and polar codes (SC and SCL). The experiment considers state-of-the-art codes.

The efficiency of a coding scheme in correcting a maximum number of errors in a wireless communication setup determines its effectiveness. The tested coding schemes show comparable performance. However, the simulation results demonstrate that LDPC codes outperform convolutional, polar, and Reed-Muller coding schemes for larger block-length codes. Additionally, it is observed that a subclass of LDPC codes, specifically AR4JA, performs better than regular AR3A codes. All the decoding algorithms for ARJ4A achieve a bit error rate (BER) floor level of 10-9.

In conclusion, the comparison of error correction codes (ECCs) in this study highlights that while all codes offer some level of error protection, their effectiveness varies depending on different circumstances. Therefore, selecting the most suit-able code for a specific application is crucial based on its ability to detect and correct errors. Future work could explore further optimizations and advancements in 5G wireless communication error-correction coding schemes.

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An Assessment of the Roadway Segment Environment influence on Traffic crash in Oyo State Nigeria

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Abstract Traffic crashes remain a critical global issue. Governments have introduced measures such as legislation, driver education, and improved road design to address this challenge. This study examines highway traffic collision data from Federal Road Safety Corps (FRSC) records (2020–2022), integrating georeferenced maps, road networks, satellite imagery (Landsat, Google Maps), Shuttle Radar Topography Mission (SRTM) data, and field survey data from blackspot road segments. Analysis, which was done in ARCgis 10.8 environment, identifies 66 blackspots across 18 federal routes, with 56 curved sections linked to these routes. The findings reveal a strong correlation between environmental terrain and crash occurrences. The study advocates for the strategic placement of road signs and symbols and highlights the necessity of leveraging Global Positioning System (GPS) and Geographic Information System (GIS) technologies for accurate traffic data collection and analysis, particularly in complex terrains. These recommendations aim to enhance roadway safety and inform evidence-based policymaking.

Keywords Traffic Crashes, Blackspot, Geo-reference, Roadway environment

JEL L91, O18, R42

1. Introduction

Transportation by road is the most available mode of transportation available to mankind. It provides services at door step level unlike other modes such as air, rail, maritime and pipeline as such road network is the most intensely utilised globally, effort to organise movements on the roadways lead to improvements such as tarred roads, markings and signage's among other rules and regulation that guides its safe operation. In spite of these efforts road traffic crashes (RTCs) represent a significant worldwide challenge causing substantial morbidity and mortality, "an average of 1.19 million people die each year from road traffic crashes globally" (WHO, 2023).

Movements along the roadway may be loosely divided into two categories; people and cargo, the categorisation of these movement types is ensured in many nations by permit requirements and safety laws. Just as a horse or an ox can go down a road, so can a car, truck or motorbike. While passengers may be transported by car or bus for mass transit, cargo can be delivered by trucking firms. Modern roadways are calibrated to accommodate these various types of movement and are often distinguished by well-marked lanes, signs and other roadway characteristics to enhance road safety. "Nigeria has the largest road network in West Africa, with a national network of roads currently estimated to be about 194,200 km of which 129,580 km (or 66.7%) are local and rural roads, 30,500 km (15.7%) are state-owned roads, and the federal government owns 34,120 km (17.6%)" (Lamidi, et al 2022).

Where road traffic crashes repeatedly occur at a specific location on the roadway segments, such a location is referred to as blackspot. The Victorian blackspot programme, which started in Australia in 1980 defined blackspot as a location or a roadway segment where at least 12 casualties of road traffic crashes have occurred in 3 years. (Road Safety International 2020) What could be responsible for the development of blackspots? What could be wrong with these locations? Could it be that the roadway segments.

Roadways are constructed across different types of landforms and land uses; some roadway sections could be hilly or valley-like or undulating and some on straight, flat land. Blackspots are also formed along these different terrains. The purpose of this study is to determine whether there is a relationship between roadway traffic crash occurrences and the physical condition in terms of the terrine on which these roads are constructed.

1.1. Study Area

Located in the southwestern region of Nigeria, Oyo State is notable for its agricultural significance, cultural diversity, and historical importance. It is bordered to the north by Kwara State, to the east by Osun State, to the south by Ogun State, and to the west by the Republic of Benin. The capital of Oyo State is Ibadan, which stands as one of the major cities in Nigeria. The terrain of Oyo State is varied, with rolling hills in the north and west and fertile plains in the south. The undulating landscape in the northern Oke-Ogun region is well known. The Oyan River is a major river, while the Ogun River makes up a section of the state's northern frontier. Oyo State's tropical climate results in distinct wet and dry seasons. In general, the rainy season runs from April to October, while the dry season runs from November to March. Oyo State is mostly an agrarian state, with a largely agricultural economy. Among the several road networks that comprise the state are major thoroughfares that link Oyo State to neighbouring states and cities.

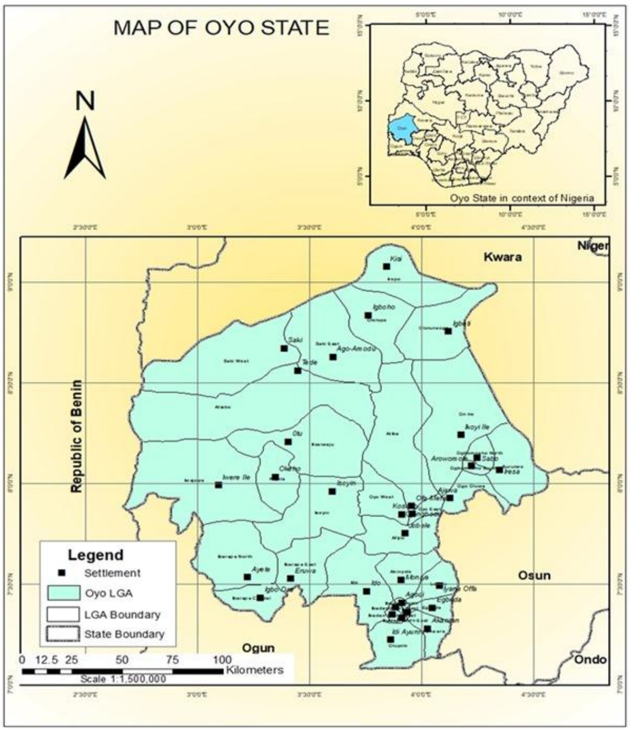

Figure 1. Oyo State Map.

According to Road Safety International 2020, when the Victorian blackspot programme started in Australia in 1980, it stated that "a blackspot is a roadway segment of 1 km with at least 12 casualty traffic crashes in 3 years." A casualty crashes means a crash that resulted in death or injuries, or a crash in which at least one person is injured (seriously or slightly). There have been great successes in traffic crash reduction over 40 years (an 85% reduction in traffic crashes, according to their definition). These blackspots may be an intersection, a curve or bend, or a straight stretch of road. To investigate these blackspots, this chapter emphasises, research design, data Characteristics, data sources and collection methods, calibration and description of variables and method of analysis.

2. Methodology

2.1. Data Procurement

This study adopted an ex post facto research design, with data obtained from Federal Road Safety Corps (FRSC) Oyo State sector (2020-2022). a secondary data derived from the (FRSC) traffic crash records spanning the years 2020 to 2022. This record was as a non-spatial data and could not be used in the GIS environment. As a result, the FRSC data was converted to spatial data and made usable in the GIS environment. A field survey was conducted at the blackspot road segments in the study area, as guided by the FRSC data, to ascertain the environmental conditions of these blackspot road segments and to create an attribute table to record the characteristics and conditions of the various blackspot road segments using GPS and locating places with goggle earth and Landsat imagery.

Information that was already captured from the roadway environment that is available in landsat imagery was used to extract the route in the study area. The elevation of the study area was obtained from a shuttle radar topographic mission. This enabled us to know the height above sea level of the blackspot segment and it was used to create the relief map. This also added to our understanding of the topography on which the roadway segment is constructed. The important data elements from this FRSC record include the following (attribute data) listed:

1. Date of traffic crash
2. Time of occurrence.
3. Location/route described in km to or from.
4. Type of traffic crash (non-injury, injury and death)
5. Causes of traffic crash.
6. Number of people involved in the traffic crash
7. Weather condition at the time of traffic crash
8. Speed limit on the blackspot segment.

The Landsat imagery of the study area was imported into the ArcGIS 10.8 environment, where geographic data essential for the research, including road networks, were digitised and extracted. The attribute table created to record the characteristics and physical condition of the various blackspot road segments during the field survey was introduced into the ArcGIS 10.8 environment in a Microsoft Excel sheet, along with the needed portion from the Federal Road Safety Commission records. The types of data, characteristics and source data for the curvature analysis are described in Table 1.

Table 1. Types of Data, Characteristics and the Sources

Types of Data	Scale	Date	Activity	Source
Geo-referenced Map of Oyo State	1:25000	2020		Office of surveyor general Oyo state.
Satellite image (Landsat)		2020		United State Geological Survey (USGS)
Shuttle topo-graphic mission data (SRTM) for terrain analysis		2020		United State Geological Survey (USGS)
Blackspot road segments	Geo-coding and Data Extraction location/route description	2022/23	Field Survey	Federal road safety corps traffic crash records as a guide.
Road/Street Network Map	Geo-coding and Data Extraction (Road Net-work)	2020	Vectoring from Imagery	African Regional Institute for Geo-spatial Infor-mation Science And Technology (AFRIGIST)
Road traffic crash data		2020/22		FRSC.

The approach offers descriptive and statistical methodologies with GIS analysis. This study fills the gaps in the use of (spatial) environmental data and methodology by using GIS to analyse road traffic crashes in blackspot locations, overcoming the limitations of using only statistical methodology. Insights into the influence of roadway environmental element on road traffic crashes were enhanced, offering valuable information for policymakers, transport planners and urban planners to improve road safety. The descriptive research design systematically describes the characteristics of the data concerning road traffic crashes and roadway environmental element. This involves identifying and categorising various environmental element and summarising the data to provide a clear picture of the current situation.

The statistical research design examined the correlational between different variables, specifically how roadway environmental elements (independent variables) are related to the frequency and severity of road traffic crashes (dependent variables). It helped to identify significant relationships and potential causal links between environmental element and road traffic crashes.

Geographic Information System (GIS) analysis enabled the spatial examination of crash data and the environmental element allowing for the visualisation and identification of spatial patterns. Maps were created as visual representations of the data to highlight key findings. For example, the maps showed crash blackspots and the visualisation of crash fatalities in relation to road surface quality. GIS analysis provided a spatial dimension to the research, revealing geographic patterns and correlations that might not be evident from statistical analysis alone. This helped in identifying the specific locations and conditions that are high-risk to inform targeted interventions.

2.2. Methods of Analysis

The method of data analysis for this study is a combination of two methods, which are:

1. Geographic information system (GIS)
2. Statistical methodology.

This study utilised a combination of Geographic Information System (GIS) analysis and statistical methods for the examination of data. The Geographic Information System method of analysis using Arcgis 10.8 software. Spatial analysis of roadway traffic crash occurrences, statistical method of analysis was used to find the correlation of relationship between road traffic crashes and the roadway environmental elements. The objectives and the associated methods of analysis are hereby linked and explained:

2.2.1. Geographic information system (GIS)

1a. Blackspot (Getis-Ord G*): This is for studying the identifiable spatial patterns, detecting spatial clustering of activities and statistically identifying significant spatial concentrations of high and low values associated with geographic features. This was demonstrated in a study by Songchitruksa and Zeng (2018), "Getis-Ord spatial statistics to identify blackspots". The Getis-Ord G* statistic is a variation that includes the point itself in the calculation making it a more localised measure. It is measured by collecting spatial data points with attribute values and their spatial coordinates, creating a weights matrix based on spatial proximity (e.g., inverse distance or binary adjacency). This is executed using ArcGIS 10.8 and the result is displayed in the form of a thematic map representation.

1b. Geographically weighted regression: This model explores the spatial relationship between the dependent variable (traffic crashes) and one or more independent variables (environmental element) using the regression analysis model. This was demonstrated by (Ali et al. 2018) in a study titled "Application of Geographically Weighted Regression Technique in Spatial Analysis of Fatal and Injury Crashes". The process involves gathering spatial data with coordinates, choosing a kernel function, selecting the bandwidth, calculating weights for nearby locations and performing a weighted least squares regression to estimate local regression coefficients. Executed using ArcGIS 10.8 and the result displayed in the form of a thematic map representation.

The two map product is then overlaid to produce a thematic map showing where environmental element is significance in the occurrence of traffic crashes in the study area.

Road curvature analysis

Road curvature analysis of the roadway was conducted using the ROCA (Road Curvature Analyst) software, integrated as an ESRI ArcGIS Toolbox. This tool facilitates the processing of vector (line) data. The identification of curves is achieved through the application of the Naïve Bayes classifier, which assists in determining the angles or radii of roadway curvature to ascertain the corresponding design speed limits. This objective stems from a classification approach for effective identification of road geometry introduced by (Andrasik et al. 2020) "Identification of Curves and Straight Sections on Road Networks from a Digital Vector Data".

In the ArcGIS 10.8 environment, the input data includes road section ID, X coordinates, coordinates of polyline vertices, Y coordinates, and geometry classification—where 0 represents a tangent and 1 signifies a horizontal curve. The analysis is performed using the ROCA analysis toolbox within ArcGIS 10.8. This software efficiently fragments roadway system data into tangents and horizontal curves, automatically calculating the circles of the horizontal curves and the azimuths of the tangents.

The overlay operation within the GIS environment was utilised. This operation is a crucial and powerful tool in GIS, as it superimposes spatial and attribute information from multiple thematic map layers to generate new insights. Curvature analysis is overlaid on elevation data (SRTM), land use data of the study area, roadway data, traffic crash black-spot data and Oyo State boundary data. The analysis produced a thematic map of roadway sections under study for the susceptibility or criticality of the roadway curve segments to road traffic crashes and proneness to road traffic crashes.

2.2.2. Statistical methodology

The Pearson Product-Moment Correlation Analysis is a statistical technique employed to assess the strength and direction of the linear relationship between two continuous variables. This statistical technique was applied to Hypotheses 5, to find the correlation between roadway segment elevation and traffic crash occurrences. The measure of correlation is called the correlation coefficient. The degree of relationship is expressed by the coefficient which ranges from correlation ($-1 \leq r \leq +1$). The direction of change is indicated by a sign. The correlation analysis enables us to get an idea of the degree and direction of the relationship between the two variables under study, it does not imply causality. Pearson's correlation analysis was applied in the study "identification of traffic accident-risk-prone areas under low lighting conditions". The study seeks to evaluate the effect of low lighting conditions on traffic accidents in the city of Cluj-Napoca. To analyse the degree of dependence between lighting and the occurrence of traffic accidents, Pearson's correlation coefficient was utilised. Furthermore, the relationship between the spatial distribution of traffic accidents and lighting conditions was assessed using the frequency ratio model. (Ivan et al., 2018). The Pearson Product-Moment Correlation Analysis was executed in the SPSS environment.

3. Locations of Traffic Crash Blackspots

The table below (Table 2) reflects the data obtained from the FRSC showing the number of blackspots on each of the location and the year respectively.

Table 2. Roads and Location with Traffic Crash Blackspots.

S/n	ROUTE	Location Of Blackspot (road sections)	Number of Blackspot	2020	2021	2022	Number of RTC
1	Ibadan Metro	Bodija Juction, Iwo Road Roundabout, Eleyele Baptist Church and Adegbayi	4	57	72	52	229
2	Elebu	Benjamin Area, Ologuneru Police Outpost, Mobil Filling Station, Iyana Ijokodo	4	70	136	101	457
3	Ibadan -Abeokuta	Ida Village, Onigbagbo Village, Omi Area	3	79	88	46	213
4	Ibadan-Ife	Best Option Egbeda, Asejire, Idi Omu Area, Olorunsogo, Egbeda,Olope Meji	6	227	393	366	1305
5	Ibadan-Ijebu Ode	Top One Area, Quarry Area, Idi Ayunre Round About	3	69	73	43	185
6	Ibadan-Iwo	Alagbede, Iyana Offa, Olodo Bridge	3	89	81	59	229
7	Ibadan-Lagos	Gurumaraji, Dominion University, Onigari, Ajanla Farms, Nasfat Junction, Oriental Foods, Sawmill	7	437	703	563	2154
8	Ibadan-Oyo	Akinyele, Iroko Village, Ilora Bridge, Jobele, Fiditi, Tose, Koladaisi University	7	350	622	522	1918
9	Iganna - Okeho	Oke Afin Iganna	1	22	12	5	39
10	Kisi-Igbeti	Ojukoto	1	1	15	3	29
11	Ogbomosho-Ikoyi	Odo Oru, Idi Araba, Oloko Produce Warehouse	3	9	14	22	69
12	Ogbomosho-Ilorin	Aaseleke, Igbin Village, Kara Express, Oja Waso, Under Bridge	5	33	67	71	206
13	Ogbomosho-Oshogbo	Okin Apa.Abede, Gomal College	3	92	87	35	214
14	Ogbomosho-Oyo	Onigari, Busari Village, Sekona, Asani, Agric, Ajaiya	6	296	223	229	748
15	Oyo-Metro	Olivet School, Durbar, Owode, Kosobo	4	157	125	142	424
16	Oyo-Iseyin	Eleekara, Ado Awaye Area, Agunrege	3	40	15	32	87
17	Kisi-Ilorin	Irepo Junction, Olorunsogo Area	2	9	3	3	15
18	Saki-Ago Are	Aljassas Rd,	1	22	9	14	46
	TOTAL		**66**	**2059**	**2738**	**2308**	**8567**

This table 2 is further reflected in the graph or chart as shown in Figure 2.

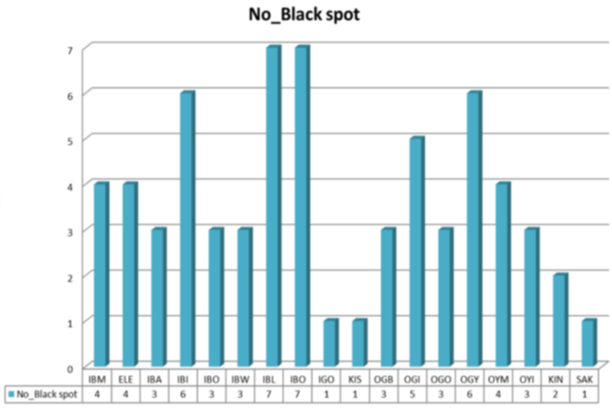

Figure 2. Blackspot Chart.

The chart shows a chart that Ibadan to Lagos, Ibadan to Oyo, Ibadan to Ife and Ogbomosho to Oyo have the highest number of blackspots and by implication, the highest number of road crash frequency.

The location of these blackspots in reality is depicted with the thematic map in figure 3, below.

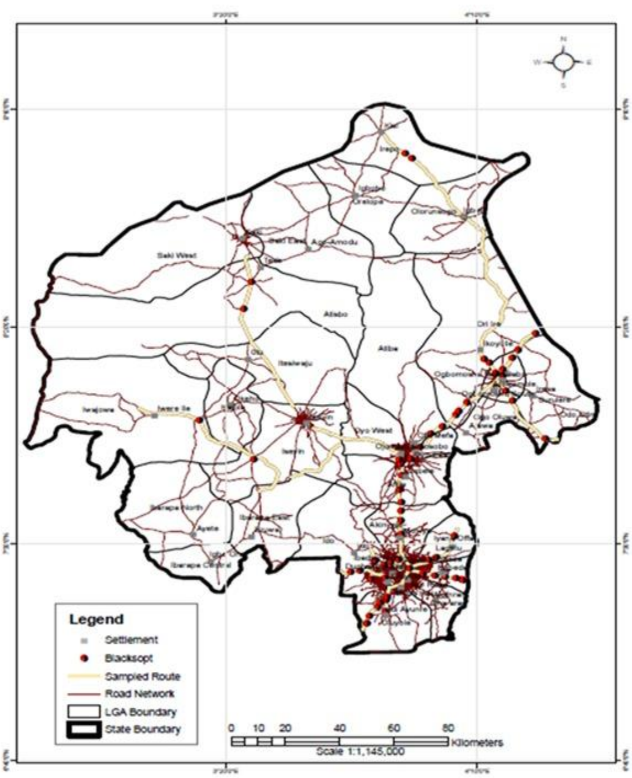

Figure 3. The Map of Oyo state showing blackspots.

The road segments with the red dots in fig.3.3 is the location this study investigated, with a view to finding out the unique conditions that have made such road segment a blackspot for road traffic crashes.

4. Results and Discussions

4.1. Land use Landcover analysis

Land use landcover plays an essential role in modelling roads that are prone to traffic crashes. On a particular axis, the probability of a road experiencing a traffic crash in built-up area is different from that of a forested area. The probability of a road traffic crash along the routes under study is modelled according to the land use and land cover. The landuse-landcover thematic map representation of the study area is shown below (Figure 4).

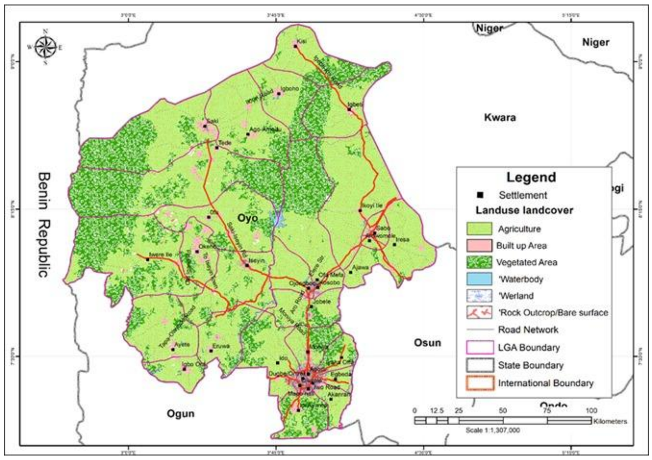

Figure 4. Land use landcover in the study area.

4.2. Terrain Analysis

Terrain analysis was carried out to identify the roadways that are prone to traffic crashes among the roadways under study. It involved the use of elevation and other topological data in order to analyse the road that is prone to traffic crashes. The elevation and slope data along with the route were obtained from the analysis of SRTM (shuttle radar topographic mission) data; in the ArcGIS environment, the elevation and slope of the study area, respectively.

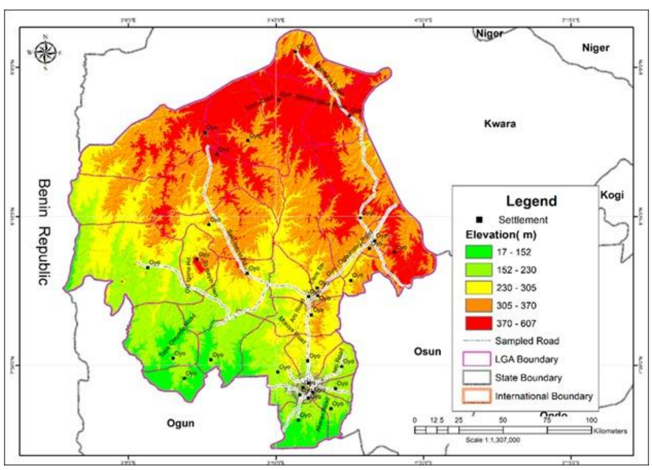

Figure 5. Elevation of study area the as generate from SRTM data

Oyo State's landscape is a gentle, rising slope, with the lowest part in the southern part between 17 and 152 meters and the highest part in the northern part at about 600 meters above sea level. With this type of terrain traffic crashes are on the rise because a large part of the road sectors that make up the state's road network are developed on sloppy terrain which means that moving from the south to the north will involve climbing the hilly terrain while moving north to the south will involve descending. In whatever direction, care must be taken and roadway countermeasures must be put in place to make the road safe.

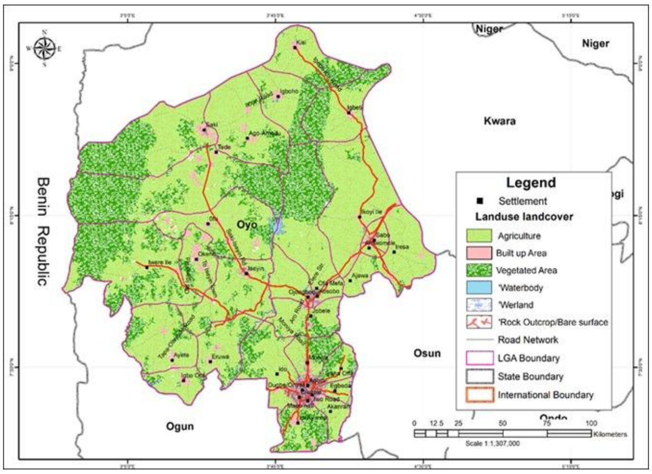

Figure 6. Slope of the study area

Slopes are the manifestation of variation in the elevation, which is a major factor that determines the design speed of roadways and hence once the speed limit for such roads is not obeyed a traffic crash is likely to occur. These roads are characterised by inadequate or lacking road shoulders as could be seen in the northern part of the state because of the elevated terrain.

4.3. Spatial Significant of environment factor on road traffic crash

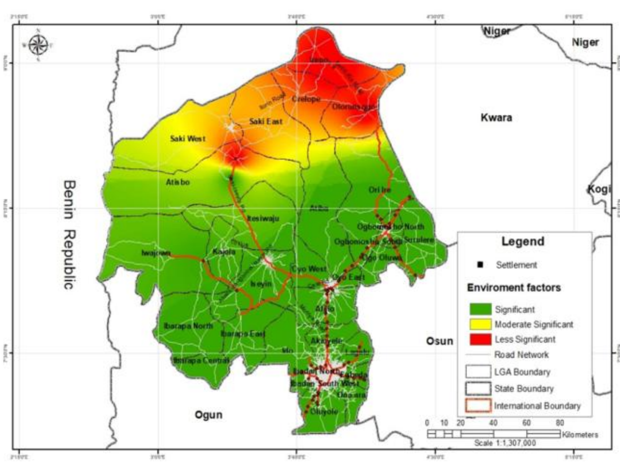

Figure 7. Spatial significant of environment element on road traffic crash

This thematic map (Figure 7) depicts the overall outlook of traffic occurrences across the study area. This is a product of the overlay operation in the GIS environment. The roadway traffic crash occurrence is superimposed on the geographic weighted regression analysis and the result shows that the effect of environment factors is significant in the southern part of the state represented by green, while environment factors are less significant in suburbs especially in the northern part of the state represented by red. A moderate region exists between the north and the south coloured yellow.

4.4. Roadways prone Traffic crash

The analysis to identify roadways prone to traffic crashes due to roadway environmental element is obtained using the weighted overlay analysis of the environmental element considered above (elevation, land use and contour). The environmental element was overlayed and reclassified according to their influence on the road traffic crash. The land use landcover ranked highest, followed by elevation and slope and the contour served as a vector back for the elevation raster. The overlay analysis results show that the sections of the route within the built-up area are less prone to traffic crashes while the sloppy and elevated areas are more prone. The plane areas are moderately prone. The outcome of the environment overlay analysis is shown below (Figure 8).

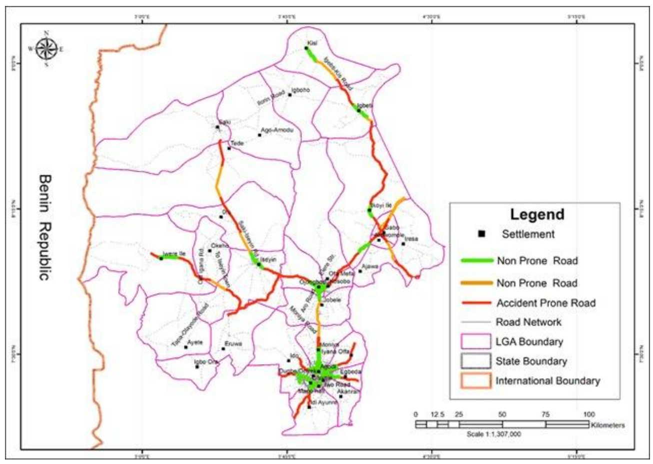

Figure 8. Roads that is prone to traffic crash in the study area

Also observed from the result in Fig. 8 is that the routes tend to be safer as they enter the buildup areas and increase in un-safeness as they move away from the buildup areas. Observing the green-coloured sections of the roadway on the map. This may be as a result of improved roadway environmental conditions due to road maintenance within the urban area, a further analysis is represented in table 3 and figure 9 respectively.

Table 3. Analysis of the road prone to road traffic crashes in km.

S/n	Road crash probability	Length (Km)
1	Non-Prone Road	231.34
2	Moderate Prone	134.34
3	Traffic crash prone Road	461.98

Table 3 shows the total length of roads that are prone to road traffic crashes within the route study. 231.34 km is safe and not prone 134.34 km is moderately prone and 461.98 km of the route under study is prone to road traffic crashes. The graphical representation of these findings in a pie chart is shown (Figure 9):

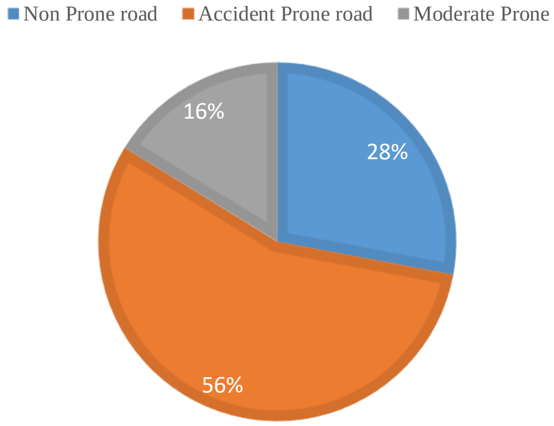

Figure 9. Analysis of road that prone to traffic crash along the study route

This suggests that more than half of the length of the route under study is not safe due to the terrain of the construction as made obvious by the colours. Segmenting the road lengths into non-prone, moderately prone and prone to traffic crash occurrences it is observed that the red colour, which is 56 percent of the total length of roads under study is found to be prone to road traffic crashes.

4.5. Relationship between roadway segment elevation and traffic

There is no significant relationship between roadway segment elevation and traffic crash occurrences. In finding the relationship between blackspot height values in metres obtained in the GIS environment using the SRTM data, which gives a slope or elevation value. This data is used to measure the correlation which is called the correlation coefficient. The degree of relationship is expressed by coefficient which ranges from correlation ($-1 \leq r \geq +1$). The direction of change is indicated by a sign. The correlation analysis gives us an idea of the degree and direction of the relationship between the two variables which are the blackspot elevation in height and traffic crash occurrence.

Table 4 shows the elevation values of roadway segments within a blackspots and the frequency of the traffic crash occurrences used for correlation analysis.

Table 4. Black spot (road sections) elevation to traffic crash frequency

Location of Black spot (road sections)	Elevation (DEM Value) in meter	Frequency of traffic crash occurrences
Bodija Juction	222	78
Iwo Road Roundabout	229	75
Eleyele Baptist Church	184	40
Adegbayi	212	36
Benjamin Area	186	160
Ologuneru Police Outpost	219	99
Mobil Filling Station	156	116
Iyana Ijokodo	207	82
Ida Village	193	70
Onigbagbo Village	189	56
Omi Area	154	87
Best Option Egbeda	185	267
Asejire,	186	301
Idi Omu Area	162	251
Olorunsogo	201	271
Olope Meji	204	321
Top One Area	129	51
Quarry Area	130	71
Idi Ayunre Round About	115	61
Alagbede	205	66
Iyana Offa	198	86
Olodo Bridge	192	76
Gurumaraji	140	307
Dominion University	148	280
Onigari	155	327
Ajanla Farms	157	324
Nasfat Junction	164	315
Oriental Foods	168	298
Sawmill	155	300
Akinyele	252	270
Iroko Village	291	298
Ilora Bridge	306	278
Jobele	277	250
Fiditi	267	274
Tose	247	268
Koladaisi University	299	280
Oke Afin Iganna	224	39
Ojukoto	384	29
Odo Oru	335	32
Idi Araba	320	28
Oloko Produce Warehouse	318	36
Aaseleke	346	35
Igbin Village	375	52
Kara Express	381	41
Oja Waso	351	47
Under Bridge	343	30
Okin Apa.	319	77
Abede	369	65
Gomal College	319	71
Onigari	320	125
Busari Village	287	138
Sekona	277	110
Asani	291	124
Agric	335	148
Ajaiya	300	100
Olivet School	311	106
Durbar	320	98
Owode	311	114
Kosobo	339	112

Eleekara	287	38
Ado Awaye Area	216	29
Agunrege	333	20
Irepo Junction	354	8
Olorunsogo Area	406	7
Aljassas Rd	329	45
Saki-Ago Are	291	46

This is a negative correlation coefficient of -0.426 between elevation and frequency of traffic crash occurrences which indicates that as one variable increases the other tends to decrease and vice versa. Although the magnitude of the correlation coefficient suggests a moderately negative relationship with the correlation coefficient at -0.426 and the p-value stated at <0.01). This suggests that higher elevations are associated with fewer traffic crash occurrences, we therefore reject the null hypothesis (H_0) which states that there is no relationship between roadway segment elevation and traffic crash occurrences and conclude that there is a significant correlation or relationship between roadway segment elevation and traffic crash occurrences; this relationship does not imply causality but a mere relationship or correlation.

Table 5. Correlation Table

	Elevation	**Traffic crash**
Elevation		
Pearson Correlation	1	- 0.426**
Sig. (2-tailed)		0.000
N	65	65
Traffic crash		
Pearson Correlation	- 0.426**	1
Sig. (2-tailed)	0.000	
N	65	65

The study systematically examined the influence of roadway environmental elements on road traffic crashes in Oyo State, fulfilling its stated objectives. Findings indicate that traffic crashes occur across all roads in the state, with 66 blackspots identified along 18 routes. Routes such as Ibadan-Lagos, Ibadan-Oyo, Ibadan-Ife, and Ogbomosho-Oyo recorded the highest crash frequencies, with blackspots concentrated on 18 sections along the Ibadan-Ife, Ibadan-Lagos, and Ibadan-Oyo routes, exhibiting crash frequencies of 21, 27, and 36, respectively.

The study highlights the significant role of environmental factors, particularly terrain, in influencing crash occurrences. The state's landscape comprises a gentle slope rising from 17–152 meters in the south to about 600 meters in the north. Roads traversing this terrain, especially on sloping sections, are prone to crashes due to the challenges of ascending and descending slopes, coupled with inadequate road shoulders, particularly in elevated northern regions.

Traffic safety is better in built-up urban areas, where enhanced roadway maintenance mitigates crash risks. Conversely, crash proneness increases in rural or vegetated areas, with 56% of the 827.66 km of roads studied classified as prone to crashes. A pie chart representation reveals 231.34 km as safe, 134.34 km as moderately prone, and 461.98 km as highly prone to crashes.

A statistically significant but moderate negative correlation (r = -0.426, p < 0.01) between elevation and crash frequency was observed, suggesting that higher elevations experience fewer crashes. However, this relationship indicates correlation rather than causation. Consequently, the null hypothesis asserting no relationship between elevation and crash occurrences is rejected. These findings underscore the need for terrain-sensitive roadway countermeasures, including improved signage, speed regulation enforcement, and enhanced road shoulder design, to mitigate crash risks across the state's road network.

5. Conclusion

This study underscores the critical influence of roadway environmental factors on traffic crash occurrences in Oyo State. The identification of 66 blackspots across 18 routes, with higher crash frequencies concentrated on key intercity routes such as Ibadan-Lagos, Ibadan-Oyo, and Ibadan-Ife, highlights the urgent need for targeted interventions. The findings reveal that sloping terrains, inadequate road shoulders, and poor road conditions significantly contribute to crash risks, particularly in northern, elevated regions of the state.

While urban areas benefit from improved safety due to better road maintenance and infrastructure, rural and vegetated areas remain disproportionately vulnerable. The analysis demonstrates a statistically significant negative correlation between elevation and crash occurrences, suggesting that while higher elevations may experience fewer crashes, the challenge lies in navigating the slope transitions.

To address these challenges, strategic recommendations include enhancing road signage and speed control measures, especially on sloping terrains, and improving road infrastructure, such as widening shoulders and implementing slope stabilization measures. The adoption of advanced technologies like GIS and GPS for precise crash mapping and data analysis is also essential for informed policy-making and proactive road safety management.

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