IOSR Journal Of Humanities And Social Science (IOSR-JHSS)
Volume 28, Issue 12, Series 3 (December, 2023) 33-41
e-ISSN: 2279-0837, p-ISSN: 2279-0845.
www.iosrjournals.org

Multivariate Analysis Techniques As A Tool To Support Vehicle Routing: A Contribution To The Planning And Management Of Urban Passenger Transport

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Abstract:
Background*: The high concentration of inhabitants in urban centers causes considerable inconvenience to urban mobility. Faced with this scenario, urban passenger transport becomes a highly relevant issue for any society. As well as this concentration being disorderly, in most cases there are inevitably problems such as major traffic jams, directly affecting the population's movements. Because the composition of transport is highly heterogeneous, the profile of the urban transport user has many dimensions and variables, making it complex. Within this context, the routing of bus lines has an important influence, as it contributes significantly to congestion.*
Materials and Methods*: For these reasons, this study, seeing the need to encourage the emergence of balanced urban transport solutions, proposed a hybrid approach involving multivariate data analysis techniques and the Geographic Information System for Transport (GIS-T) to help route vehicles, which can contribute to the planning and management of urban passenger transport. To this end, a survey was carried out in order to support a Structural Equation Model (SEM) that points out dimensions and variables, which were used to draw up hypotheses that supported the construction of routing for a bus line.*
Results*: The hybrid approach involving multivariate data analysis techniques and the Geographic Information System for Transportation (GIS-T) has resulted in a solution that contributes to vehicle routing. This allows for a dynamic analysis in the modeling of different vehicle flows and Travel Generating Hubs (TGPs). This can be replicated for occasions involving different vehicles.*
Conclusion: *As a result, the reliability measure computed is correlated with the change in travel time of the Origin-Destination pair, since an increase in travel time reduces reliability.*
Key Word*: Structural Equation Modeling. Geographic Information System for Transportation. Simulation*

Date of Submission: 02-12-2023 Date of Acceptance: 12-12-2023

I. Introduction

The agglomeration of people in cities around the world has had a severe impact on urban transport. At the same time, accelerated urbanization and the motorization of people's movements have had a direct impact on sustainable development in cities. Within this context, it is common to find stakeholders from different public and private sectors working together on projects to plan and operate urban passenger transport systems (Reiffer et al., 2018). However, according to Angelidou et al. (2018), the large number of interrelationships between dimensions and variables that influence simulation parameters and, consequently, the definition of routes, make decisions involving the agglomeration of people in the urban environment complex.

Costa et al. (2017) state that the appropriate use of an urban transport system, considering the constant evolution of the urban population mass, is a broad and unavoidable challenge. For these authors, as the population grows, there is a need to develop mechanisms and tools to help plan and manage this system, which should consider preserving the environment and ensuring social inclusion. According to Freitas et al. (2015), the composition of the urban transport system is complex because it involves OD (Origin-Destination) matrices of passenger (private, public and private), freight and goods trips, each with their own interrelationships of dimensions and variables that define one or more travel matrices in cities.

Thus, the planning and management of the urban transport system for better efficiency requires adequate vehicle routing, which must consider the composition of the complexity of journeys from the perspective of passengers (Shen et al., 2018). Sun and Chuí (2018) point out that planning and managing the routing of bus lines makes it possible to improve supply conditions in terms of urban mobility. In the opinion of Naja et al. (2018), routings involving public transport should be analyzed considering the possible interrelationships of the dimensions and variables that make up the various scenarios. For these authors, the possible causal relationships observed can clarify and indicate alternatives that help in the management and operation of public transport.

Considering the context presented and indications from the literature (Najaf et al., 2018; Shen et al., 2018; Sun & Cui, 2018), this study used Structural Equation Modeling (SEM) as the analytical method used to investigate interrelationships between dimensions and variables that contribute to the definition of urban bus routes. This choice was based on the work of Gonçalves (2016), who points out that SEM is an important tool that helps to explain the complex relationships between dimensions and multiple variables, which are exogenous (independent variables) and/or endogenous (dependent variables) and also to estimate the direct and indirect relationships between them. Another important reason for the choice, highlighted by this author, is the breadth of analysis provided by the set of techniques present in multivariate data analysis (SEM), such as multiple regressions, path analysis, factor analysis and analysis of covariance.

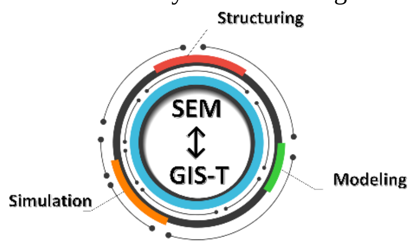
This research therefore contributes to the literature on urban passenger transport planning and management by proposing a hybrid approach that aids vehicle (bus) routing. This approach involves the use of multivariate data analysis techniques (Structural Equation Modeling - SEM) to analyze the interrelationships between dimensions and variables that influence route preferences, as well as a Geographic Information System for Transportation (GIS-T) to simulate scenarios. To operationalize the application of this approach, a bus line in the municipality of São Mateus (Espírito Santo - ES) was used as the research unit.

II. Material And Methods

According to Ramirez and Seneviratne (1996), the planning of public transport networks must be based on knowledge of stakeholder needs. For these authors, this knowledge involves investigating and analyzing the dimensions and variables that influence urban transport. For Salles (2013), routing is essential when managing and planning transport networks. The author points out that by simulating scenarios, it is possible to adjust alternatives that meet the needs of all stakeholders.

The municipality of São Mateus, located in the northeastern microregion of the state of Espírito Santo (ES), was chosen as the research site due to its logistical importance for the state and surrounding municipalities, which are home to a number of players that influence urban passenger transportation, such as multinational companies, universities, colleges, educational institutes, hospitals, among other demand-generating hubs. In addition to these players, important investments are planned for this municipality, such as the establishment of factories in various segments and a deep-water port. Taking these elements into account, the methodological approach of this study was developed in three stages (Figure 1). This approach began by structuring the problem, followed by modeling and simulating scenarios.

Figure 1 - Summary of methodological steps.



Source: Authors (2023).

Initially, sets of dimensions and variables that influence the planning and management of urban passenger transport were identified in the literature, and it is worth noting that this characterization was done by means of a bibliometric study. At the same time as this activity, the company that holds the concession for the urban bus service in the municipality of São Mateus (ES) and the municipal office responsible for it selected a bus route considered to have a high volume of use during business hours, in order to simulate scenarios.

Thus, having delimited and characterized the dimensions and variables, as well as identifying the bus line that will serve as the research unit, the population was characterized based on the IBGE demographic census (2010). After this characterization, the sample size was defined using the formulation (Equation 1) proposed by Dupont and Plummer (1990). Based on these elements and the characterization of the population, the data collection instrument was drawn up and its application began.

$$n = \frac{N \cdot Z^2 \cdot p \cdot (1-p)}{Z^2 \cdot p \cdot (1-p) + e^2 \cdot (N-1)}$$

(1)

Where *n* is the calculated sample; *N* represents the population; *Z* is the standardized normal variable associated with the confidence level; p symbolizes the probability of the event; and *e* is the sampling error.

After this, a survey was carried out among users of the selected line in order to select a set of dimensions and variables that would contribute to better use of the line. Multivariate analysis techniques (SEM) were then applied to analyze consistency and select the dimensions and variables that would make up the modeling of the problem, thus concluding the first stage of the methodological approach with this procedure.

Next, the modeling stage (second stage) began with the location and analysis of the trip-generating hubs that influence the selected bus line (demand, characteristics, stops, headway, direction of travel, among other parameters that will be used in the simulation). With this in mind, and based on the set of dimensions and variables selected, hypotheses were formed to help develop the routing model.

Finally, the third stage of this work (simulation), taking into account the modeling carried out, carried out the routing of the line, using a Geographic Information System for Transport (GIS-T) and also carried out analyses of this routing. Based on the set of dimensions and variables selected, alternative scenarios (routings) were developed.

The data obtained from the questionnaires was processed using the statistical software SPSS (Statistical Package for the Social Science) Statistics Desktop 24.0, trial version, to help minimize errors. The data analysis was initially prepared by checking and treating missing values and outliers to avoid possible discrepancies. In addition, the AMOS (Analysis of MOment Strutures) 25.0 trial version software was used to help operationalize the SEM. This software was selected because its graphical interface allows for better interaction with the results, as well as allowing for the elaboration, visualization and adjustment of structural equation models. TransCAD software version 6.0 was used to draw up the routes and analyze the scenarios.

III. Result

For the initial stage, identification of dimensions and variables, a bibliometric survey was carried out to collect the main works related to the research topic, from which the dimensions and variables were selected (Table 1).

Table 1 - Summary of the bibliometric survey.

Dimension	Variables	Author(s)
Quality of an urban public transport system (QUAL)	*Accessibility* (ACESS)	Aslam e Batool (2017); Šojat et al. (2017).
	Trip duration (DUDV)	Šojat et al. (2017); Mohamed et al. (2017); Eung e Choocharukul (2018).
	Reliability (CONF)	Aslam e Batool (2017); Eung e Choocharukul (2018).
	Frequency (FREQ)	Šojat et al. (2017); Mohamed et al. (2017); Eung e Choocharukul (2018); Aslam e Batool (2017).
	Occupancy (OCUP)	Eung e Choocharukul (2018); Aslam e Batool (2017).
	Condition of vehicles (ESTDV)	Šojat et al. (2017); Mohamed et al. (2017); Eung e Choocharukul (2018).

Source: Authors (2023).

In order to select the bus line that served as the research unit, the main deciding factor was the number of passengers during business hours, i.e. the flow of passengers. In line with the previous selection proposal, the five lines with the greatest flow were selected, and the line with the greatest flow was the 12:10 p.m. schedule, whose initial route is Guriri via Praiano, bound for the Federal Institute of Espírito Santo (IFES)/Federal University of Espírito Santo (UFES). The large flow of passengers on this line can be explained by the fact that there are two major centers generating trips, which are the higher and secondary education institutions IFES and UFES.

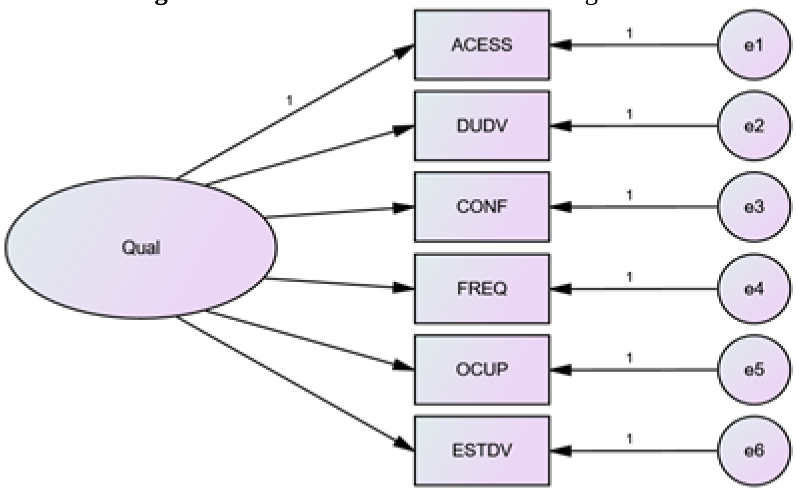
According to the calculations of Dupont and Plummer (1990), the population of the municipality of São Mateus - Espírito Santo, the location of the research unit, had a sample of 384 people. The data collection instrument was a structured questionnaire, which was evaluated by experts in the field. The questionnaire was applied by e-mail, and the data was treated using the Kolmogorov-Smirnov normality test with 95% reliability, in order to remove outliers and missing values.

The interrelationships between the dimensions were then investigated. Using SPSS software, the answers obtained from the survey were adjusted according to Table 1.

The relationships between the dimensions were checked using a path diagram to see if they were significant. This stage was carried out using the AMOS software, in which Confimatory Factor Analysis (CFA) was performed. Based on the model's ability to reproduce the interrelationships of the set of dimensions and variables in the sample, the overall quality was assessed. In this way, each variable was fixed to its respective dimension by means of paths.

According to the theoretical measurement model (Figure 2), the research hypotheses were drawn up. These were formulated according to the conditions of causality represented in the SEM theoretical measurement model. Thus, all the relationships between the variables and the dimensions were constructed for later use in developing the roadmap modeling.

Figure 2 - Theoretical model for measuring SEM.



Source: AMOS (2023).

According to Šojat et al. (2017), the number of urban circular vehicle lines influences the use of the public transport system, so that with a greater number of bus stops, thus increasing accessibility to users, the population would tend to use this service more, however this factor is related to several others linked to the infrastructure of such a system. Aslam and Batool (2017) follow the same line of thought, taking into account the viability of some of the lines studied in their research. Eung and Choocharukul (2018) also point out that there is informal, door-to-door transportation whose accessibility is more suitable than public transportation, thus showing the great importance of accessibility, the bus stops, for a quality public urban transportation system. The first hypothesis is therefore

H1. Accessibility (ACESS) has a positive effect on the Quality of an urban public transport system (QUAL).

Šojat et al. (2017), point out that urban mobility is directly linked to a good public urban transport system, thus indicating that such a service must be attractive in the eyes of users, and report that the speed of operation, duration of the trip, is extremely important for the quality of the public urban system. Mohamed et al. (2017) also report on this topic, using smart card data collected by automated fare collection systems, thus being able to compare different factors linked to urban mobility, among them the duration of journeys. Thus, the second hypothesis is:

H2. Trip duration (DUDV) has a positive effect on the Quality of an urban public transport system (QUAL).

Aslam and Batool (2017), carried out a study to check urban mobility, analyzing costs and the performance of some bus lines, in this way, the number of lines and their respective operating hours were analyzed, thus showing that for the quality of public urban transport the cost, flexibility of lines and reliability, translated into the number of lines and schedules available are important variables for such a study. Eung and Choocharukul (2018) compare public urban transport with informal transport, which is considered door-to-door and has a wide variety of timetables, and is therefore reliable because it does not provide delays to users, thus reporting that reliability must be treated as an essential variable for the quality of the public urban transport system. The third variable is therefore

H3. Reliability (CONF) has a positive effect on the Quality of an urban public transport system (QUAL).

Šojat et al. (2017) together with Aslam and Batool (2017), highlight frequency, time between bus tickets, as an important supporting variable, from the point of view that for users of the public transport system it is advantageous to have a wide range of schedules and little waiting between vehicles. The fourth hypothesis is therefore

H4. Frequency (FREQ) has a positive effect on the Quality of an urban public transport system (QUAL).

Eung and Choocharukul (2018) together with Aslam and Batool (2017), report the importance of occupancy, i.e. the capacity to serve users along the route, so that the quality of the urban public transport system tends to be met to the extent that all users are collected without overloading the capacity of the vehicle fleet. However, the capacity can remain the same, but the increase in operating speed and space savings for passengers can be improved and thus the quality of the system can improve (Aslam & Batool, 2017). Thus the fifth hypothesis is:

H5. Occupancy (OCUP) has a positive effect on the Quality of an urban public transport system (QUAL).

Aslam and Batool (2017) report the importance of the condition of the vehicles used in the urban circular transport service for retaining users. According to these authors, the population is directly influenced by the condition of the cars used in such a service, and as the general condition of the buses is poor, users tend to use other means of transportation, such as private vehicles, and thus, as a result, traffic tends to become worse. The same authors present the real conditions of the vehicle fleet at the research site. According to them, around 35% of the buses have poor speedometers, tires, floors and roofs. So the sixth hypothesis is:

H6. Vehicle condition (ESTDV) has a positive effect on the Quality of an urban public transport system (QUAL).

As some of the paths in the measurement model showed little correlation, adjustments had to be made to the theoretical SEM model. It was therefore necessary to re-specify the SEM measurement model. To do this, the indications and observations provided in the pilot test by experts in the field were taken into account, so adjustments had to be made to the dimensions with the lowest correlations. Thus, the measurement model was simulated and altered several times, re-specifying versions of this model (Table 2), until the unacceptable and bad values were no longer present. These versions were analyzed by removing dimensions and variables whose paths showed low correlations.

Table 2 - Model quality measurement indices.

Respecified version	Dimensions removed	GFI	AGFI	RMSEA
V1	ACESS and OCUP	0.921 (Good)	0.645 (Unacceptable)	0.245 (Unacceptable)
V2	ACESS, OCUP and CONF	0.977 (Good)	0.881 (Poor)	0.123 (Unacceptable)
V3	FREQ, CONF and OCUP	0.941 (Good)	0.723 (Unacceptable)	0.201 (Unacceptable)
V4	DUDV, FREQ, CONF and ESTDV	0.993 (Very Good)	0.956 (Very Good)	0.085 (Acceptable)

Source: AMOS (2023).

This result suggests a consistent fit of the model, indicating that there is no notable difference between the observed and estimated variable matrices. This shows that V4 was the most effective way of reproducing the covariance matrix of the observed variables. In this case, the Accessibility and Reliability dimensions stand out, thus providing positive quality indices for the SEM theoretical model.

In order to build the current scenario, the study area was georeferenced. The starting point for this stage was the location and generation of an image of the research area, the municipality of São Mateus located in the northeastern micro-region of the state of Espírito Santo (ES), using the Google Earth Pro tool, which was adjusted to the Universal Transverse Mercator (UTM) coordinate system and the unit of measurement in meters.

From the previous location, some coordinates, which served as base coordinates for vectorizing the research area, were collected and inserted into the AutoCAD 2018 student version software. The image of the research area, obtained in JPEG format, was inserted and the entire area was vectorized according to the base coordinates. The final digital map file (Figure 3) was saved in .dxf format and imported into TransCAD.

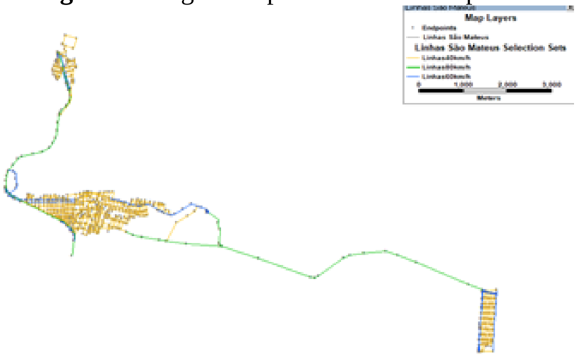
Figure 3 - Digital map.

Source: TransCAD (2023).

The georeferenced file was used in TransCAD, but to do so, it had to be adjusted to the unit in meters, UTM (Universal Transverse Mercator) coordinate system, UTM zone 24, GRS 1967 ellipsoid and adjusted to the southern hemisphere. All the settings were made to ensure that the measurements, location of the research area and calculations used in the software were correct.

The transportation system was modeled by adding some important information obtained from Google Maps, namely: street directions, speed limits and travel times based on maximum road speeds and distances (Figure 4). Both parameters were added through selections provided by TransCAD. Maximum road speeds were classified based on the actual speeds defined for the city. These are: 60 kilometers per hour in blue, 80 kilometers per hour in green and 40 kilometers per hour in yellow.

Figure 4 - Digital map with maximum speeds.



Source: TransCAD (2023).

Travel times were added based on equation 2:

$$T = D/V \qquad (2)$$

In which:

T → Travel time;
D → Track distance;
V → Maximum track speed.

The headway (H) of the time slot of the line studied was calculated (Equation 3), in minutes, by dividing the total minutes of the slot by the frequency of journeys established for it:

$$H = T/F \qquad (3)$$

H → headway;
T → minutes in the track;
F → frequency of trips.

The next step was to create a route file, which enabled the selected circular bus line to be illustrated. However, before creating this file, it is necessary to create a network file, which allows the software to analyze the described network. The route file was named "Bus Route" (Figure 6).

Figure 6 - Creating a route file.

Source: TransCAD (2023).

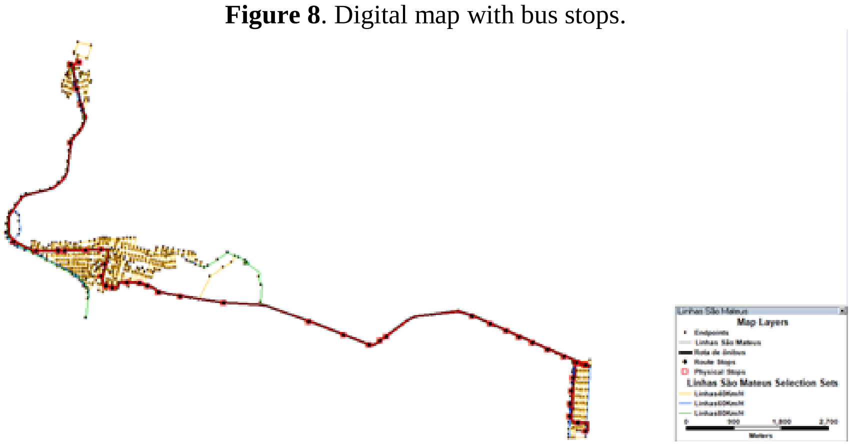
The bus line studied has been illustrated in TransCAD (Figure 7), according to the current route of the current bus line.

Figure 7. Bus line.

Source: TransCAD (2023).

When you create a route system in TransCAD, it allows you to create stops, "Route stops" and "Physical Stops", which can characterize the bus stops on the line studied. This way, the bus stops for passengers to board and alight were added (Figure 8). Stop times, the time the bus remains stationary for alighting and boarding, were calculated from an average of 39 observations.

Figure 8. Digital map with bus stops.



Source: TransCAD (2023).

As the current scenario was built in TransCAD, important information was obtained that served as a benchmark for comparison with the proposed scenarios, so that the improvements could be verified. This information can be seen in the distance traveled between the bus's initial and final destination, the headway (41.20 minutes), the journey time (39.45 minutes), and the number of stops (41), which are the points where passengers board and disembark.

The alternative scenario, whose accessibility and reliability dimensions were used, translates these characteristics into the number of boarding and disembarking points, the possibility of vehicle delays, and the number of available bus schedules (Aslam & Batool, 2017; Eung & Choocharukul, 2018). In this way, possible changes to the flexibility of the bus line were represented, such changes being an increase in the number of boarding points and a decrease in the number of alighting points. Based on this assumption, the journey time was changed to 44.45 minutes, the headway to 41.20 minutes and the stops changed to 46.

As the number of bus stops increases, it can be seen that the journey time increases by around 5 minutes. However, the flow of passengers tends to increase and so more users will be served, but this increase in flow can have an impact on the occupancy dimension, causing inconvenience and overcrowding. Therefore, an improvement in the cars of the company providing the service should be studied.

The possibility of reducing the number of bus stops was also illustrated, thus verifying that journey times were impacted and reduced. However, users tend to travel longer distances to use the services, which can cause inconvenience among service users. To get around this, the headway could be reduced (41.20 minutes), thus causing an increase in the number of vehicles per hour on this line (journey time: 36.45 minutes; stopping points: 36); however, a cost study should be carried out.

IV. Conclusion

Physical interventions such as works on urban roads are unavoidable activities on any road network, and the analysis in the literature generally focuses on the impacts around the site analyzed. However, this work considers the effects on a micro scale, i.e. on sensitivities across the entire traffic network of a bus route, and analyzes the impact of interventions on travel times. In the literature, road works in irregular condition are identified as the main culprits in causing variation in the distribution of travel times, which consequently alters the distribution of bus line reliability.

The aim of this work was to propose a hybrid approach to assist in the planning and management of urban passenger transport, involving multivariate data analysis and vehicle routing techniques, since it was possible to represent different conditions in the day-to-day operation of a bus line. The specific contributions resulting from this work are: establishing the influence of vehicle type characteristics on the route; traffic flows are influenced by behavioral models of vehicle driving and pedestrian circulation and are not based exclusively on roadway behavior.

Thus, by adopting a hybrid approach involving multivariate data analysis techniques and the Geographic Information System for Transportation (GIS-T), it was possible to develop a solution that contributes to vehicle routing. Due to its constructivist nature, this solution can be used by professionals in the sector, public managers and companies to plan and manage urban passenger transport. The proposed approach allows modifications to be made to its operational structure and, as a result, solutions to be customized for different cases. In addition, the use of multivariate data analysis techniques in conjunction with GIS-T allowed for dynamic analysis in the modeling between different vehicle flows and Trip Generating Poles (PGV's). This analysis can also be replicated, especially in cases involving passenger vehicles, freight vehicles and urban buses, generating different space-time profiles for each trip made within a transportation network.

The results showed that the overall reliability of travel time at the network scale is likely to decrease with the adjustment works on the supporting infrastructure, especially when it comes to the headway. It was also noted that each proposed scenario had a different impact on selected Origin-Destination (OD) pairs (bus routes), indicating the need to evaluate alternative proposals for undertaking these adjustment works. Although some OD pairs showed a slight improvement in travel time reliability, most of the others are expected to have reduced reliability, and the travel time on the most affected OD pair will be three times worse compared to the existing condition without support infrastructure adjustment works. This observation points to the need to carry out an impact analysis on a wider network scale, rather than limiting the analysis to the local vicinity. Finally, the results also showed that the computed reliability measure is correlated with the change in travel time of the OD pair, especially since an increase in travel time reduces reliability.

Acknowledgements

We thank the Operations Research Laboratory, Logistics and Transport of the Federal University of Espírito Santo/ University Center North of the Espírito Santo by the academic and technical support in the design and development of this work.

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