Developing a GIS for Rural School Transportation in Minas Gerais, Brazil

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Abstract – This Report aims to give a detailed account of the study of rural school transportation in Minas Gerais and propose a routing method to create better routes to attend rural students and schools. The federal government of Minas Gerais launched a three-year program to establish new school bus lines in rural parts of the state. This government project's goal is to give better access to basic services such as schooling in poorer areas of the country in order to contribute to their development and make their life conditions better.

The situation of rural school transportation in Brazil is shown in this paper. The analysis of the conditions of school transportation and comparison with school transportation in other countries, such as the United States or France, will show that action is necessary for the development of rural areas of the state.

This will bring to introduce the new federal government project that aims to create new school bus lines around the state to guarantee better access to education. In this very important project, which has many different universities and private companies are working on, the Universidade Federal de Minas Gerais, with the Transport laboratory NucleTrans, held by Pr. Marcelo Franco Porto, has been given the task to establish a routing method to be used on the municipalities concerned by the project, and establish a methodology.

In order to understand how a methodology can be established for school bus routing, it is necessary to contextualize the different existing methods for solving the Vehicle Routing Problem (VRP). Thus, the focus was turned upon the heuristic methods that are able to find a "good" solution to the problem.

The performance of the heuristics was tested for the city of Governador Valadares. The results of this test were also discussed in this paper.

Keywords –Intelligent Transportation System; Rural School Transportation; GIS; Metaheuristic Algorithms.

I. INTRODUCTION

Many municipalities in the state of Minas Gerais offer students transportation to and from schools; however, this transportation is precarious in many cases and requires actions and from the State Government [1].

In deed, in spite of its considerable size, most of Brazil's economic activity is concentrated in small areas. While these areas remain in the spotlight because of economic and political reasons, rural areas have been often been ignored by social policies resulting in a lower life quality and poor access to public services such as school transportation.

Both the Secretary of Education and the Ministry of Education in partnership with UFMG have proposed the project, and many other different organizations sponsor the project.

To start the research, is necessary to answer, in parallel, to the following problem: What methodology is used for the implementation of School bus routes? This has brought us to first establish a diagnosis of rural school transportation and then to study routing problems.

The subject of school transportation being quite precise, not many articles or books are available on the subject and most treat only the case of developed countries, with good infrastructures such as good quality roads and accessibility.

II. RURAL SCHOOL TRANSPORTATION IN BRAZIL

Rural school transportation ensures the basic need of education in rural areas. Providing this transportation proves to be a great challenge for public authorities today [2, 3, 4].

7 432 543 elementary students ride a school bus (2006 School Census) [5] provided by the state and the municipal public authorities. This figure takes into account 4 661 602 rural students: 17% of them attend schools under state jurisdiction and 83% of those students attend municipal schools. There are currently 53 028 928 students that attend public elementary schools. Rural pupils represent 14% of the total amount of school bus riders in Brazil [3].

Rural school transportation has many bad aspects: great distances, badly maintained vehicles, old vehicles, overcrowding, and lack of appropriate infrastructures [6]. The bus rides usually take a very long time, which shows the lack of proper routing. 30% of routes are longer than 50 km. Routes lasting between 60 and 90 minutes represent 32.4% of all routes. Routes with riding times over 2h represent 13.7% and these include routes sometimes lasting more than 4h [4].

The average age of vehicles used for school transportation is 15 higher than 15 years and many vehicles that are over 70 years are sometimes used for school transportation [2].

III. Rural School Transportation in France and United States

In most developed countries, the United States or France for example, the majority of schools has their own school bus (or the school district assigns school buses exclusively to one school). A school bus only picks up students from one school. This is called a single load problem and makes up most of the literature on the subject mainly because school transportation research has focused on developed countries.

The main problem with rural school transportation in France [7, 8] comes from the general tendency of urbanization and peri- urbanization which has lead the rural areas (82% of territory but only 23% of the population) abandoned. As a result of this mutation many school have closed, forcing students out of their communes in order to access education. Public funding has also been reduced, creating costs for the families.

The number of pupils riding in school buses in the United States has been rising since the last fifty years. Today, 22.5 million children take the school bus every day and around 500 000 school buses are used for the transport. This transport method is still considered to be the safest means of transport in the United States [9, 10, 11].

IV. Federal Government Project

This project's main objective is the analysis of the rural school transportation in the State of Minas Gerais, in order to support the National Support School Transport and the Way to School Program. Among the other goals are the optimization of the use of financial resources, the improvement of the methodology use for conducting surveys, the standardization of the vehicles used for school transportation, and other actions related to school transportation.

The project comprises in four distinct steps. The first step refers to the geoprocessing of transport routes in rural schools. Municipalities will be selected for this geo-processing according to certain established criteria. This step will also be set to scan the database in order to process the information of the field of research. Therefore, this includes the development and acquisition of special software for digital database.

In a second stage will begin the process of team training and operation management for the cities and municipalities. This step will include the production of a specific course.

The third step compromises the testing of interventions proposed by the Technical Report, included those aimed at team training management and operations.

Finally, the fourth step will be based on tests performed in the previous steps and will aim at optimizing the different routes in the system.

This project covers over 250 municipalities in Minas Gerais and will be distributed in 10 administrative regions. The estimated time for this entire project is estimated to be around 3 years.

V. The Vehicle Routing Problem

The Vehicle Routing Problem (VRP) [12, 13, 14] is a combinatorial optimization and integer-programming problem [15]. It is part of transport problems such as the Traveling Salesman Problem (TSP) [16, 17] or the Chinese Postman Problem (CPP) [18]. All these problems concern logistics of one or many vehicles that need to cover a certain grid of transport to deliver merchandise to specific clients. The most interesting aspects of the study of VRP are the economies generated by the solutions. In deed, transport costs represent usually between 10 and 20% of the final price in any given merchandise. Using VRP methods of optimizations, these costs are reduced by an average of 5 to 20%.

Mathematical Formulation

The mathematical formulation I will present here is used in integer programming. It translates the natural model of the problem with binary variables and is quite easy to understand.

Let $G = (V, E)$ a graph, orientated or not, where $V = \{v_1, ..., v_n\}$ is a vertex modeling the n cities, or the clients, and $E=\{(v_i, v_j): i \leq j; v_i\, v_j \text{ in } V\}$ is a set of edges, routes, linking the nodes and cities together.

Let x_{ijk} be equal to 1 if the vehicle k passes through the arc (v_i, v_j), simply noted (i, j) in the rest of the model. We next add the node $v0$ to the set V, which corresponds to the depot. We also suppose that the graph $G = (V, E)$ is a complete graph, i.e. all the nodes are connected. This means all the cities can be visited from one single city.

The other constants of the problem are the following:

n : the number of clients (nodes)

m : the number of vehicles

Q : the vehicle capacity

qi : the demand of client i

cij : the costs of passing through the arc (i , j) going from i to j (distance of time)

The decision variables of the problem are the variable x_{ijk} mentioned earlier:

$$x_{ijk} = \begin{cases} 1 & \textit{if vehicle k passes through } (i,j) \\ 0 & \textit{else} \end{cases}$$

With these different variables, the optimization problem of the CVRP can be written as:

$$(1) \quad \textit{Minimise} \quad \sum_{i=1}^{n}\sum_{j=1}^{n} c_{ij} \sum_{k=1}^{m} x_{ijk}$$

Subject to:

$$(2) \quad \sum_{i=1}^{n}\sum_{k=1}^{m} x_{ijk} = 1 \quad \forall 1 \le j \le n$$

$$(3) \quad \sum_{j=1}^{n}\sum_{k=1}^{m} x_{ijk} = 1 \quad \forall 1 \le i \le n$$

$$(4) \quad \sum_{i=1}^{n}\sum_{l=1}^{n} x_{ilk} = \sum_{l=1}^{n}\sum_{j=1}^{n} x_{ljk}$$

$$(5) \quad \sum_{j=1}^{n} x_{0jk} = 1 \quad \forall 1 \le k \le m$$

$$(6) \quad \sum_{i=1}^{n} x_{i0k} = 1 \quad \forall 1 \le k \le m$$

$$(7) \quad \sum_{i=1}^{n}\sum_{j=1}^{n} x_{ijk} \le Q \quad \forall 1 \le k \le m$$

$$(8) \quad x_{ijk} \in 0,1 \quad \forall 0 \le i, j \le n; 1 \le k \le m$$

Under this formulation, (1) insures the optimization problem minimizes the sum of the transport costs.

Constraints (2) and (3) insure that each client is delivered once and constraint (4) insures the conservation of the flow. Constraint (5) makes sure that the run starts and ends at the depot. Constraint (6) is the capacity constraint and constraint (7) and (8) insure the binary nature of the variable x.

Parameters

Many different variables of the VRP exist. In deed, a more general formulation of the VRP is: the optimal conception of routes by a fleet of vehicles, bases in one or many depots, in order to deliver a set of clients (or cities) geographically dispersed with known orders [19]. This definition puts forward parameters that characterize variants of the VRP. Among these parameters are: the transport network, the customers, and the vehicle fleet. Other constraints can also be added to the problem. Finally one of the most important parameters resides in the objective function to be optimized.

Principal variants

Here are the three most common variants of the basic VRP:

- the VRP with capacity constraints (CVRP or capacitated VRP) ;
- the VRP with time windows (VRPTW);
- the VRP with pick-up and deliveries (VRPPD) ;
- the VRP with distance constraints (DCVRP) ;

These variants are not independent to one another, since the VRPTW and the VRPPD are both extensions of the CVRP.

SOLUTION METHODS FOR THE VRP

Like all optimization problems, the VRP has been studied and solved using exact algorithms, specific heuristics and metaheuristics. These three families correspond to the general classification of resolution methods for the VRP.

Exact algorithms

Exact algorithms, also called complete algorithms, find the optimal solution to the optimization problem by exhaustively exploring all the possible solutions (or configurations). This type of algorithm is the most basic but is generally inappropriate for solving combinatorial problems.

Heuristic Algorithms

By definition, a heuristic is a way to guide the choices made by an algorithm in order to reduce its complexity [20]. A heuristic is specific to certain problem and cannot be generalized.

Usually, heuristics are based in a “neighborhood” concept, which means how several existing intuitive resolution processes are structured. Two common ways of organizing the local search in the neighborhoods are:

- VND – variable neighborhood descend – that uses use a fixed hierarchy of neighborhoods;
- RVND – Random Variable Neighborhood Descend – that uses Neighborhoods randomly.

Both ways were embedded into two perturbation strategies:

- VNS - Variable Neighborhood Search – it consists in a pre-defined bond of perturbation executions and local search (VND or RVND)
- ILS - Iterated Local Search – it also consists in a bond of perturbation executions and local search (VND or RVND) which is repeated for a maximum number of iterations. At each iteration a neighborhood is randomly selected to generate a disturbance.

The combination of the two forms of local search with two perturbation strategies resulted in four different heuristic methods. Besides these, another method was considered, known as RTR - Record-to-record travel that consists of two phases. The first is the construction of an initial solution, and the second performs local search row by row iteratively.

Metaheuristic Algorithms

Metaheuristics can be seen as more “powerful” and “evolved” heuristics in the way that they can be generalized for larger families of problems [21]. Metaheuristics are usually ranked in function of the set of solutions they handle: some find a unique solution such as Tabu Search [22] while others offer a set of solutions such as Genetic Algorithms. These algorithms are all very different.

VI. SUPPLEMENTARY STUDY OF ROUTE OPTIMIZATION

PROBLEM CHARACTERISTCS

The problem consists in a set of students scattered over a geographic region, in need to be transported to their respective schools before the beginning of their classes, and go back home afterwards. The goal is to allocate vehicles to transfer these students with minimum routing and transportation costs, and yet to offer an adequate level of service to students.

GOVERNADOR VALADARES

Governador Valadares is a micro-region of Minas Gerais encompassing 25 municipalities. Most of these municipalities are in rural areas and have a low-life quality making this small region a good candidate to develop a routing strategy for the government project. There are 62000 students in the municipality.

DEVELOPMENT OF THE WORK

Researches regarding the creation and optimization of routing models to be applied in GIS Rural Transcolar were developed. This work will provide innovative solutions, besides those already developed and implemented for the process of rural school transportation. Two types of routing arrangement rural school were selected for the context of Minas Gerais, which showed a less complex routing management, in addition to having lower costs than other routing types. The selected route types are:

1. Routing by school
2. Routing with vehicle sharing

Regarding type 1 (Routing by school) the routes of heterogeneous fleet are created for each school separately. Each school has its exclusive fleet and cannot transport students from other schools.

For type 2 (Routing with vehicle sharing) the vehicles are allowed to transport students from different schools. As a result, more than one school is visited when required by the same vehicle.

METHODS OF RESOLUTION

Due to the high number of students, the resolution of the problem through mathematical methods was discarded because of its combinatorial nature and computational complexity. Thus, the focus was turned upon the heuristic method that is able to find a "good" solution to the problem.

In all of the five heuristic implemented methods, the initial solution is created from the adapted “Clarke and Wright” algorithm [23]. This method generates viable routes concerning the economy generated when gathering different student routes.

COMPUTATIONAL RESULTS OBTAINED SO FAR

It was developed five C/C++ codes to the resolution of each route type. Those codes were parameterized in order to allow data entry, such as: identification of the types of vehicles available, fixed cost per vehicle type, geographical location and identification of each school and student and each student’s school.

PERFORMANCE OF THE HEURISTICS FOR THE PILOT TEST GOVERNADOR VALADARES

To test the performance of the five developed resolution methods, they were applied in a pilot instance provided for Governador Valadares.

In the computational experiments, the following performance metrics were computed:

% Best: This value represents the percentage of times that the best solution was found for each course confronted by the current method with other methods. It considered all executions of methods for all instances.

% DevMed: is related to the accuracy of the method. It is presented in percentage and calculated by the average of the deviations of the results for each instance in each execution and the best overall results of the five methods for each instance.

% DevMin: is related to the accuracy of the method. It is presented as a percentage of the average deviation between the best result obtained by the method in 30 executions for each instance and the best overall results of the five methods for each instance.

ScoreMed: indicates how many times the average of other method achieved better results than the method considered for each instance for each execution. A low value indicates good performance of the method. The final value is relative to the average number of tests instances of this sum score for each execution.

Chart 1 shows the average of 30 executions and the best result for each method in both types of arrangement: 1 Routing (per school) and 2 (Routing schools with vehicle sharing). The best method for type 1 was the ILS-RVND with an average cost of $ 6,751,999.82, while for type 2 RTR method had the lowest cost, $ 5,901,862.05. That was unexpected. As the obtained solutions are very close to each other and differentiated only by some monetary units, it can be stated that the obtained solutions are equivalent.

For this instance it was considered three types of vehicles. The results obtained by experimental tests are shown in tables 1 and 2 that contain the principal results of each method. Since there is only a single instance, it is required more tests with real instances in order to obtain a better performance trend of the methods.

It can be considered that the share of vehicles by students (type 2) is more interesting than the construction of routes to each school separately (type 1), as shown in Table 1.

Table 1 – Sumary of the results for Governador Valadares.

Type 1: Routing by school					
Heurística	**Best**	**Média**	**DevMin**	**DevMed**	**Score**
VNS-VND	6.752.005,51	6.795.356,19	0,0005	0,6426	75
VNS-RVND	6.752.001,27	6.765.357,57	0,0005	0,1983	49
ILS-VND	6.751.990,40	6.752.022,47	0,0003	0,0008	42
ILS-RVND	6.751.970,23	6.751.999,82	0	0,0004	14
RTR	6.752.031,10		0,0009		35
Tipo 5: Routing with vehicle sharing					
Heurística	**Best**	**Média**	**DevMin**	**DevMed**	**Score**
ILS-VND	5.901.918,44	5.901.961,98	1,0000	0,0017	54
ILS-RVND	5.901.890,13	5.901.934,61	0,0005	0,0011	15
VNS-VND	5.901.925,72	5.901.971,69	0,0011	0,0019	63
VNS-RVND	5.901.895,38	5.901.949,75	0,0006	0,0015	45
RTR	5.901.862,05		0		0

From Table 2 it can be seen that there is a decrease of 12.59% in the cost when the second type is employed. Note that the number of vehicles is significantly reduced from 38 to 24, which means a decrease of 36.84%. Although there is also a reduction in the total distance traveled 5.49% in type 2, there is a significant increase (49.64%) of the average length of the routes as well as the longer route in relation to the type 1. However the average displacement of students is reduced by 3.21%.

Reducing the number of vehicles is a positive point of type 5. In this arrangement, the vehicle fleet is more homogeneous. Besides facilitating the maintenance of vehicles, reducing labor and idleness of resources, the management of routing is less complicate.

Table 2 – Results

Aspect	T1	T5	100x(T1-T5)/T1 (%)
Total Cost	6.751.970,23	5.901.862,05	12,59
Total Distance (Km)	1.970,23	1.862,05	5,49
Average displacement per student (Km)	28,05	27,15	3,21
CPU time (sec)	6,79	164,39	-2321,06
Average of students per vehicle	24,84	39,33	-58,33
Average length of routes (Km)	51,85	77,59	-49,64
Longest route	187,31	244,45	-30,51
Number of vehicles (20 seats)	13	0	
Number of vehicles (30 seats)	8	1	
Number of vehicles (40 seats)	17	23	
Total capacity	1180	950	

The Figure 1 shows the routes created for Governador Valadares.

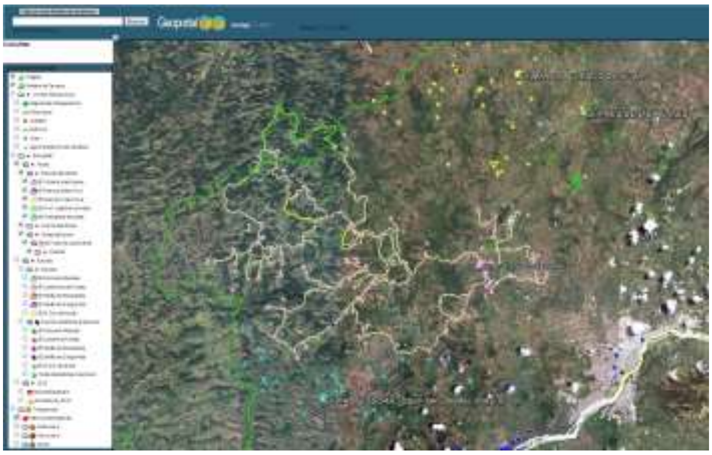

Figure 1 – A screen of developed GIS showing routes created for Governador Valadares

VII. CONCLUSION

It was observed that there is a great variability in the distances traveled on each route leading vehicles and drivers being used more than others. This requires that there be a balance between the routes. This is not the same thing as limiting the maximum distance that a route can have, since this limitation still allows small compared to other routes being run in the tax threshold.

The total distance traveled on each route in the tests conducted was not limited because of the existence of residences that are more than 90km from school in case of Governador Valadares. However, this restriction is now available for testing in other instances.

A new work methodology is also being developed which is considered besides the costs, the level of service offered to students, represented by the travel time. This type of approach is called multi-objective, where the result is expressed not as a result, but on a graph with several possibilities regarding the objectives. This approach brings a range of options to decision-maker and makes a flexible choice as this are given alternatives to decide what weight will be given to each of the functions (time or cost).which is considered besides the costs, the level of service offered to students, represented by the travel time. This type of approach is called multi-objective, where the result is expressed not as a result, but on a graph with several possibilities regarding the objectives. This approach brings a range of options to decision-maker and makes a flexible choice as this are given alternatives to decide what weight will be given to each of the functions (time or cost).

VIII. ACKNOWLEDGEMENTS

The authors thank MEC/FNDE (Ministério da Educação e Cultura / Fundo Nacional de Desenvolvimento da Educação) for the financial support for this project. We also would like to thank to Secretaria de Estado de Educação de Minas Gerais for supporting our research units and Instituto de Geoinformação e Tecnologia for technical support.

IX. REFERENCES

[1] E. A Vasconcellos, “Rural transport and access to education in developing countries: policy issues” , Journal of Transport Geography, Volume 5, Issue 2, June 1997

[2] W. L. Carvalho, R. O. M. da Cruz, M. T. Camara, J. J. Guilherme de Aragao, “Rural school transportation in emerging countries: The Brazilian case”, ELSEVIER 2010.

[3] “Perqiusa Ômnibus Rural Escolar do Brasil”,Universidade de Brasilia 2009.

[4] E. A. Vasconcellos, “Rural transport and access to education in developing countries: policy issues”, Pergamon 1997. Security Measures.

[5] IBGE, 2007. Censo escolar 2006. <http://www.ibge.gov.br/home/ >. Accessed on: mar. 2013.

[6] D.S. Chen, H. A. Kallsen, H.C. Chen, V.C. Tseng, “A bus routing system for rural schooldistricts”, Pergamon 1991.

[7] H. Fontanié, “Trajet et rammassages scolaire, Résultats d’une enquete préliminaire”, Persee 1965.

[8] “Reforme de l’organisation des transports scolaire”, Conseil General de l’ Essonne 2010.

[9] S. S. Lazarus, G. J. McCullough, “The Impact of Outsourcing on Efficiency in Rural and Nonrural School Districts: The Case of

Pupil Transportation in Minnesota", The Journal of Regional Analysis and Policy 2005.

[10] R. Ramage, A. Howley, "Parent's Perception of the Rural School Bus Ride", 2005.

[11] D. T. Williams, "The Rural Solution", Center for American Progress September 2010.

[12] M. O. Ball, C. J. Colbourn, and J. S. Provan, " Handbooks in Operations" . Research and Management Science. Elsevier, 1995, vol. Volume 7, ch. Chapter 11 Network reliability, pp. 673–762

[13] P. Toth and D. Vigo, Eds., " The Vehicle Routing Problem". Philadelphia,PA, USA: Society for Industrial and Applied Mathematics, 2001.

[14] P. Toth and D. Vigo, "Models, relaxations and exact approaches for the capacitated vehicle routing problem," Discrete Appl. Math., vol.123, no. 1-3, pp. 487–512, Nov. 2002.

[15] L. Santos, J Coutinho---Rodrigues, C. Henggeler Antunes, "A web spatial decision support system for vehicule routing using Google Maps", ELSEVIER 2010.

[16] M. Dorigo; L.M. Gambardella,, "Ant colony system: a cooperative learning approach to the traveling salesman problem," Evolutionary Computation, IEEE Transactions on ,vol.1, no.1, pp.53,66, Apr 1997

[17] R. Dantzig, R. Fulkerson, and S. Johnson, "Solution of a large-scale traveling-salesman problem," Operations Research, vol. 2, pp. 393–410, 1954.

[18] H. A. Eiselt,, Gendreau, Michel, Laporte, Gilbert. "Arc Routing Problems, Part I: The Chinese Postman Problem". Operations Research, pp.231-242, 1995.

[19] C. D. Tarantilis, D. Diakoulaki, C.T. Kiranoudis, "Combination of geographicalinformation system and efficient routing algorithms for real life distribution operations", *ELSEVIER* 2002.

[20] K. G.Zografos, K. N.Androutsopoulos, "A heuristic algorithm for solving hazardous materials distribution problems", ELSEVIER 2003.

[21] P. Schittkat, J. Kinable, K. Sörensen, M. Sevaux, F. Spieksma, J. Spingael, "A metaheuristic for the school bus routing problem with bus stops selection", ELSEVIER 2013.

[22] G. Laporte, M. Gendreau, J.-Y. Potvin, F. Semet, "Classical and modern heuristics for the vehicle routing problem". International Transactions in Operational Research, 7 (2000), pp. 285–300

[23] G Clarke, J Wright, "Scheduling of vehicles from a central depot to a number of delivery points". Operations Research, 12 (1964), pp. 568–581