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A mixed load capacitated rural school bus routing problem with heterogeneous fleet: Algorithms for the Brazilian context

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ABSTRACT

A capacitated rural school bus routing problem featuring mixed loads, a heterogeneous fleet, and the same school starting time is here addressed. This is an important problem of the routing literature which has been attracting the attention of many researchers recently. The mixed load feature allows students from different schools to ride the same bus at the same time. Five meta-heuristic based algorithms were devised to solve the problem, and evaluated on solving four different datasets, one of them being based on a real case from Brazil. Four traditional local search neighborhood structures for vehicle routing problems were adapted and specialized to handle mixed loads and a heterogeneous fleet simultaneously. To the best of the authors knowledge, it is the first time that both features are treated jointly within an algorithm, and not as a post processing optimization step. The attained cost savings and reduction of fleet sizes suggest the suitability of a mixed load, heterogeneous fleet approach for sparsely populated rural areas. Moreover the devised framework has been embedded into a decision support system which is assisting several municipalities of the state of Minas Gerais, Brazil, to better plan their routes and reduce transportation costs.

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1. Introduction

In 2013, Brazil had over 50 million students enrolled in a complex public educational system that encompassed more than 198 thousand state and municipal public schools (elementary, middle and high schools). Fourteen percent of these pupils were located in rural areas, served by multi-grade rural public schools (24% of the total number of schools). In multi-grade schools, groups of students of different grades are gathered into a single classroom and taught by only one teacher (Carvalho, da Cruz, Câmara, & de Aragão, 2010; INEP, 2013).

On one hand multi-grade schools have the advantage of having: flexible schedules, proximity to the community where they are placed, and the development of unique programs to meet students' individual needs in order to offer opportunity for them to become independent learners. On the other hand, multi-grade schools generally have the following disadvantages: inadequate facilities, poorly trained teachers, scarcity of materials, limited or no access to different types of more advanced curriculum activities, and the absence of sport infra-structure (Vincent, 1999).

Concerned with these disadvantages, the Brazilian federal government is striving to provide a better education to the rural population by encouraging and financing state and municipal authorities to close their multi-grade rural schools, and transfer those affected students to better-structured, centrally-located school facilities with single-grade classes. Several government funding programs were created to assist with this intent. One in particular, known as the *Way to School program*, is responsible for improving the daily commute of public students (state and municipal) by providing new buses – better adapted to the often severe operational conditions of the rural areas of Brazil –to the municipal administrations, which are then responsible for managing the local fleets.

However, it has been a great challenge for public authorities to manage rural school transportation services due to the lack of qualified technicians, to the great social and cultural diversity found in many regions of Brazil, and to its extensive land (Carvalho et al., 2010). As the provided resources are scarce, it has not been possible to dedicate buses to a single school, as typically found in the school bus routing literature (Park & Kim, 2010). Public

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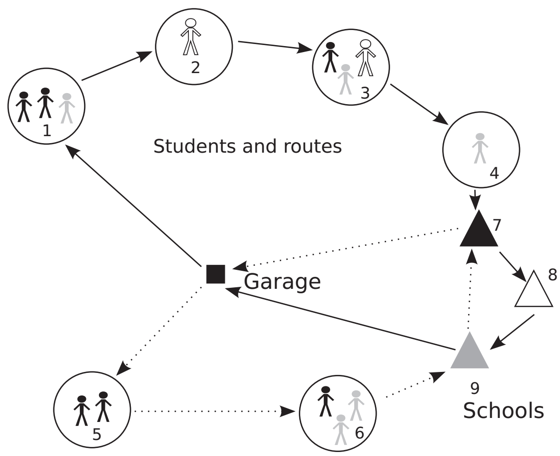

Fig. 1. Example of a school bus routing problem with mixed loading.

managers have to deal with a more complex problem in which buses are required to serve both state and municipal schools at the same time. Students from different schools ride on the same bus at the same time in order to go to their respective schools. Buses carry mixed loads of students prior to dropping them off at different destinations before returning to the garage. To complicate matters, managers often have to plan the routing for a heterogeneous fleet.

Fig. 1 illustrates an example of such a problem: Thirteen students (stick figures) scattered in six bus stops must be transported to their respective schools, represented by triangles numbered 7–9. The students are associated with each school by a color scheme, e.g. filled in stick students go to the filled in triangle, unfilled stick students go to the unfilled triangle and so on. Two bus routes, pictured as solid and dotted arrows, leave the garage (square node), and pick the students up to deliver them to their respective schools prior to return to the garage. Note that (*i*) students of different schools can ride on the same bus at the same time, (*ii*) all students are picked up prior to the delivery operation, (*iii*) each student bus stop is visited exactly once; (*iv*) each school node can be visited by more than one bus, though each bus can visit a school only once; (*v*) a bus is not required to visit all of the schools. These remarks give rise to a problem known as the rural school bus routing problem with heterogeneous fleet and with mixed loading (Park & Kim, 2010).

The mixed load assumption was first considered by Bodin and Berman (1979) who pointed out that it can occur frequently in rural areas. The authors however did not present any solution methodology to deal with it. Chen, Kallsen, and Snider (1988) also remarked that having buses to transport students of just one school at a time (single load) can result in the use of an excessive number of vehicles, especially when dealing with students living in low density areas. They devised a support decision system to aid the routing and scheduling of buses for a rural school system in which routes were manually generated.

The first authors to actually propose a computational algorithm for the mixed load bus routing problem were Braca, Bramel, Posner, and Simchi-Levi (1997). They devised an insertion procedure in which each route is constructed by randomly inserting a bus stop and its respective school at the lowest possible cost, while respecting time window and capacity constraints. The adopted objective minimizes only the number of used buses and disregards any information of routing costs. The authors also claimed, without supporting with any quantitative data, that an increase of flexibility and cost savings can be achieved whenever buses carry mixed loads.

Spada, Bierlaire, and Liebling (2005) devised a decision-aiding methodology for a bi-objective school bus routing and scheduling system with a homogeneous fleet in which the number and the types of buses are given beforehand. The framework optimizes the level of service provided by the bus operator while allowing mixed loads. The level of service is represented by two objectives: the *time loss* of the students, and the *maximum time loss*. The time loss of a student is calculated as the sum of the delay of the student and his awaiting time at the school. The delay is calculated as the difference between the actual students' journey time on the route and the minimum possible riding time for the student to get to his school. The waiting time of a student is measured as the time spent by the student waiting for classes to begin since his drop-off at his school. Initial routes are constructed by sorting the distances between each bus stop and its associated school in a non-increasing order, and then forming each route in a greedy fashion, while assuring time window and capacity constraints. A local search which exchanges bus stops from different routes is embedded into two different heuristic frameworks (simulated annealing and tabu search) to improve the initial solutions.

Park, Tae, and Kim (2012) enhanced the method of Braca et al. (1997) by devising a post improvement procedure similar to the one created by Spada et al. (2005). The addressed problem featured a homogeneous fleet, different starting school times, no routing cost information, and time window and capacity constraints. Like Spada et al. (2005), the objective was the minimization of the fleet size. A sweep based algorithm (Gillett & Miller, 1974) is used to construct an initial solution with a dedicate fleet per school. Bus stops are then reallocated, one at a time, in a greedy fashion until routes can be merged or deleted, while time window and capacity constraints are respected.

Recently, several authors investigated variants of the mixed load school bus routing problem. Bögl, Doerner, and Parragh (2015) considered the planning of school bus lines. Bus lines and not routes were planned for a homogeneous fleet. Starting at a given node, each line passes by bus stops selected from a node candidate set, before ending at some school node. Together bus lines form a connected tree. Some bus stops can act as transfer nodes when they are shared by different bus lines. To go to school, a student walks to a bus stop, rides on a bus line to his school or transfers between lines at some transfer node before reaching his school. The proposed problem was solved by an iterated local search based algorithm.

Campbell, North, and Ellegood (2015) developed a three-phase heuristic for a mixed load, homogeneous fleet bus routing problem with schools having different starting times, and with the objective of minimizing the total bus travel distance. A route was interpreted as a collection of trips, being each trip formed by a sequence of bus stops and their respective schools. Trips are first created by a Clark and Wright savings based algorithm, and then refined by a variable neighborhood descent procedure, to be later aggregated to form routes. As no strategy of solution perturbation was implemented to avoid being trap on non-promising neighborhoods of the variable neighborhood descent procedure, it is most likely that poor quality solutions were attained. Working with the same problem, Ellegood, Campbell, and North (2015) proposed a continuous approximation approach to analyze the conditions under which mixed load is likely to be beneficial in a bus routing problem. They assumed spatial density for the student demands, rather than a set of discrete student bus stops.

Kang et al. (2015) also studied the mixed load, homogeneous fleet bus routing problem with schools having different starting times, but solved it by a genetic based algorithm. Students are first clustered by a covering approach with the objective of minimizing the number of bus stops. A genetic based algorithm minimizing the total travel distance is then used to plan the routes. As infeasible

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