Optimization of Routes for Road Surface Inspection
An Application to the Portuguese National Road Network

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Abstract: Infraestruturas de Portugal S.A. (IP) is responsible for managing the Portuguese rail network infrastructure and a significant part of the road network. An annual inspection must be performed on every road segment for which IP is responsible, which sums up around 14,000 km. This is a costly operation regarding time, human and monetary resources. An optimization model that incorporates the problem technical constraints was developed and a cost analysis performed to compare the distinct scenarios that IP may face in the general layout of the inspection programme.

1 INTRODUCTION

Infraestruturas de Portugal, S.A. (IP) is a Portuguese institution with the responsibility of managing the rail network infrastructure and part of the road network in Portugal. Every year, an inspection must be conducted on the roads that IP manages, which include national roads and some motorway segments, in a total of ca. 14,000 km. The inspection is done by directly registering a few parameters related with pavement geometry and conditions, as well as other relevant road events, by moving a vehicle equipped with a device called Road Surface Tester Laser (RST) and video registering travels along the roads.

Additionally, there are technical constraints related with the maintenance and calibration of the RST device, which must be done every week in the IP headquarters in the cities of Almada or Coimbra. Another aspect concerns the inspection procedure itself: for regular roads, i.e., with both directions and at least two traffic lanes, it is assumed that road surface conditions are equivalent in both sides, and a single lane, the rightmost one, has to be travelled along. In motorways, however, both directions must be inspected. IP performs the operation usually in summertime and has implemented a travel diary that covers the entire Portuguese road network which IP must inspect, based on empirical plans adopted in previous years.

The implementation of the entire work plan is a costly operation, in time, human and monetary resources. A total of 65 working days is needed to cover the road network, at an average speed of 55 km/h. Plans are supported by spatial data stored and analysed in the institutional geographical information system (GIS), which details the geometry and attributes of the entire road network, and not only that which must be inspected. The GIS datasets have ca. 14,200 segments in total.

The goal of this work is to develop and apply a model to define the inspection routes for the road network managed by IP, which complies with the inspection technical constraints and minimizes the total cost.

2 METHODOLOGY

To achieve the expressed goals, a methodology following the steps below was developed:

- Collection and processing of road network data (namely, conversion to a format that the optimization software can handle)
- Development of an optimization model embedding the technical constraints
- Application of the model
- Critical analysis of model results.

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3 DATA COLLECTION AND PROCESSING

This section describes the data collection and processing stage, which was required to obtain and transform data from the original datasets to a format compatible with the optimization software.

IP maintains an exhaustive GIS database with the road features stored in geodatabases, providing topologically coherent datasets and at a detailed positional and cartographic scale (for instance, complex intersections such as roundabouts have their segments broken into several features).

IP also maintains a record of previous inspection routes and has established an empirical plan based on travel diaries to direct the inspection procedure. In it the travel directions are kept for future reference.

It was necessary to process these data to enable its representation as inputs to the optimization software. The first task was to consider the required level of detail for an accurate representation of road inspection plans. This implied the edition of data with a cartographic purpose to a simplified version but maintaining the topological detail: for instance, there is no need to consider all the small road segments that constitute a roundabout since there is enough detail in a description where the circular intersection is replaced with a single node on which the adjoining roads converge. Data was processed and validated manually by overlaying the geographic datasets over publicly available satellite imagery as a layer in ArcGIS (ESRI, 2011) a desktop GIS (Figure 1).

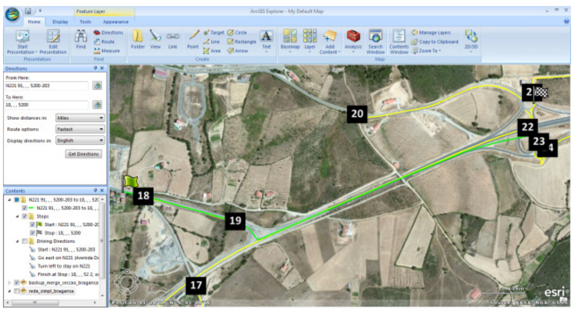

Figure 1: Processing of spatial data features: breaking converging nodes into separated nodes.

After this edition, the next task was to assign to each feature that represents a segment, which must be inspected, and to each of its two endpoints, unique identifiers. This action breaks the nodes where two or more road segments converge into several nodes. Figures 2 and 3 illustrate this operation: Node 2, which was the intersection of several road segments, of which three must be inspected, is broken into three nodes, each connecting to the respective segment.

Next, the shortest distance between each pair of nodes is calculated with the GIS software, using a network analysis function that produces an origin-destination distance matrix by applying a shortest path algorithm. The internal distances between the duplicated node instances such as the case of Figure 1 are set to zero. Note that these shortest paths may use the entire road system, i.e., they are not limited to the road segments that must be inspected.

A complete list of pairs of nodes with the corresponding shortest distance between them, which is an input to the optimization model, is then available.

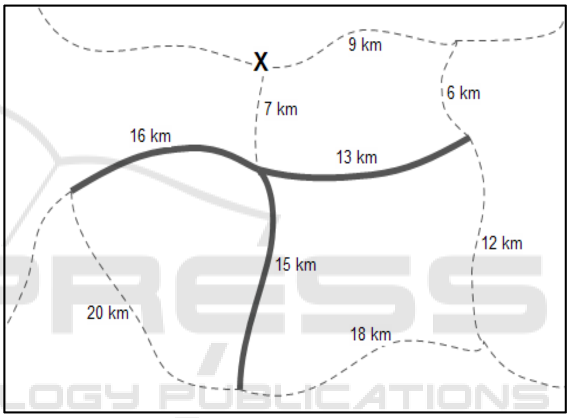

Figure 2: Processing of spatial data features: breaking converging nodes into separated nodes.

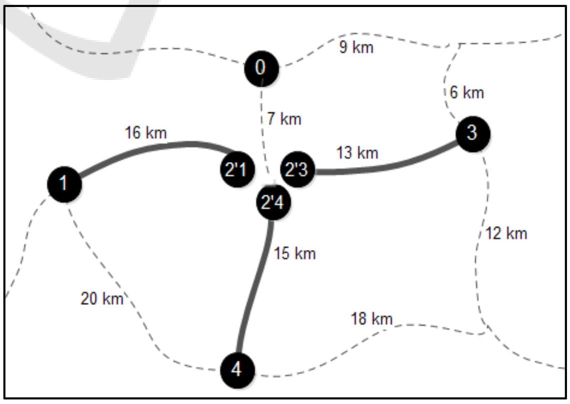

Figure 3: Processing of spatial data features: breaking converging nodes into separated nodes (continued).

4 MODEL FOR ROAD INSPECTION ROUTING

The problem under study was characterized, among routing problems, as an arc routing problem, and corresponds, in particular, to the Rural Postman Problem (RPP) were a sub-set of the arcs in a graph has to be visited (inspected).

An original linear programming formulation for the problem was developed, based on the one presented by Monroy-Licht *et al.* (2014) – model on the nodes. For sub-routes elimination, the Miller-Tucker-Zemlin formulation (Miller *et al.*, 1960, also described in Pataki, 2003) for sub-route elimination in the travelling salesman problem (TSP) was adapted to the present problem.

Decision variables are binary and equal 1 if a vertex j is visited immediately after vertex i and 0 otherwise. Auxiliary variables (integer) were included in the model to enable sub-routes elimination. Given the cost of inspecting each arc (i,j) that has to be visited, the objective function is the total inspection cost, to be minimized.

Formulations for the directed and undirected variants of the problem under study (described in the next section) were developed, as well as a mixed formulation that combines the two.

5 MODEL APPLICATION AND RESULTS

This section describes the model application to obtain optimal routes for road inspection with the existing technical constraints. The Bragança district, in the northeast of Portugal, was selected as the case study, as it presents a mixture of topological combinations of road segments to be inspected and other roads, and of short and long arcs, and thus was also able to serve as a test dataset to verify if the model constraints were able to represent feasible inspection plans. Network size was also considered adequate for a first model application.

As global parameters, values for the average inspection speed, average speed for connections (non-inspection), fuel consumption, gas price, daily wage and overnight accommodation costs were set to provide realistic values for the global operation budget.

The model was implemented in GAMS modelling system and solved with CPLEX version 12.6.1.

Table 1 presents the numeric characteristics of the model (number of variables and equations), the CPU time and the number of iterations of the branch-and-bound search to reach a solution, as well as the corresponding optimality gap.

Table 1: Summary of numeric characteristics and results of the model.

Characteristic/result	**Value**			
# variables	70,225			
# equations	71,148			
# iterations	8,128	39,348	147,303	765,369
CPU time (s)	2	10	30	60
Relative gap (%)	27.39	7.88	6.00	1.11
Absolute gap (km)	530	123	92	16

Solutions were obtained for two scenarios: (i) a model where the directions defined in the current inspection plan were fixed; and (ii) a model where road inspection directions were free. The reason to consider scenario (i) was that it might be interesting to the infrastructure manager to have an inspection plan where each road stretch is examined following the same direction of previous plans, as direct comparisons are easier to made, while (ii) might produce solutions that minimize the overall costs, without necessarily respecting the directions of previous inspection plans.

Best solutions of both scenarios were then compared with the currently implemented IP inspection plan, which was obtained empirically.

By including constraints that regulate the location of the vehicle at the end of each working day, it is possible to manage overnight stays in specific locations. Options of overnight stays either in the city of Coimbra (the closest IP headquarters) or in the city of Bragança (the district capital) were considered. Results with overnight stays are presented in Table 2.

Table 2: Results (total length and cost) and savings of solutions with overnight stays in Bragança, for both scenarios.

	Value		**Reduction %**
	km	€	
Current empirical solution	3,281	1,308	-
Fixed directions (i)	1,834	731	44
Non-fixed directions (ii)	1,718	685	48

6 CONCLUSIONS

The developed optimization model for the route inspection problem was able to produce solutions that represent significant reductions of costs when compared to the currently adopted solution.

By controlling the direction of inspection for each road segment to match the current empirical plan, savings of 44% were obtained. An additional saving of 4% is obtainable when the inspection direction is not fixed. A note should be made on these preliminary results, as the model only considered the district of Bragança while the current inspection plans are designed for a national scale where the administrative division is not taken into account. As such, these preliminary results should now be analysed by the experts in practice of Infraestruturas de Portugal.

A future development of this work is its extension to the entire country (divided by zones), to produce full-scale inspection plans comparable with the current empirical solution. Another development is the integration of the solution generator with in-vehicle systems to consider real-time unpredictable changes to the plan, e.g. due to road blockage (accidents, traffic congestion, etc.) and produce alternative work plans.

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