HAN, K., CHRISTIE, L.A., ZĂVOIANU, A.-C. and MCCALL, J. 2022. On discovering optimal trade-offs when introducing new routes in existing multi-modal public transport systems. In *Moreno-Díaz, R., Pichler, F. and Quesada-Arencibia, A. (eds.) Computer aided systems theory: Eurocast 2022; revised selected papers from the 18th International conference on computer aided systems theory (Eurocast 2022), 20-25 February 2022, Las Palmas, Spain*. Lecture notes in computer science, 13789. Cham: Springer [online], pages 104-111. Available from: https://doi.org/10.1007/978-3-031-25312-6_12

On discovering optimal trade-offs when introducing new routes in existing multi-modal public transport systems.

HAN, K., CHRISTIE, L.A., ZĂVOIANU, A.-C. and MCCALL, J.

2022

On Discovering Optimal Trade-Offs when Introducing New Routes in Existing Multi-Modal Public Transport Systems

Kate Han[1,2], Lee A. Christie[1,2], Alexandru-Ciprian Zăvoianu[1,2], and John McCall[1,2]

[1] School of Computing, Robert Gordon University, Aberdeen, Scotland, UK
[2] National Subsea Centre, Aberdeen, Scotland, UK
{k.han, l.a.christie, c.zavoianu, j.mccall}@rgu.ac.uk

Abstract. While self-driving technology is still being perfected, public transport authorities are increasingly interested in the ability to model and optimise the benefits of adding connected and autonomous vehicles (CAVs) to existing multi-modal transport systems. We propose a strategy that combines multi-objective evolutionary algorithms with macro-level mobility simulations based on publicly available data (i.e., Open Street Maps data sets and transit timetables) to automatically discover optimal cost-benefit trade-offs of introducing a new CAV-centred PT service to an existing transport system. The insightful results we obtained on a real-life case study aimed at improving the average commuting time in a district of the Leeds Metropolitan Area are very promising and indicative of our strategy's great potential to support efficient data-driven public transport planning.

Keywords: multi-modal public transport, macro-level mobility simulations, reachability isochrones, multi-objective evolutionary algorithms.

1 Introduction and Motivation

In light of the urgent need to balance environmental and economic development goals, the establishment of sustainable low-carbon mobility systems has been identified as a key target by numerous local and regional transport authorities across the globe [13, 4]. In most cases, the envisioned backbone of such environmentally friendly mobility policies is an effective multi-modal public transport (PT) system that can promote a shift away from private car use. However, the costs associated with introducing / expanding and operating PT should not be underestimated as they are often the main constraint when (re-)designing a PT system [14, 15].

Unsurprisingly, the possibility to improve existing PT systems using zero-emission connected and autonomous vehicles (CAVs) has attracted the interest of transport authorities and early test pilots indicate a relatively high level of public acceptance [12, 2]. This is because, apart from the positive environmental impact, fleets of autonomous buses and shuttles are expected to have lower deployment costs (when compared with light rail alternatives) and lower operational costs (when compared with classical buses). Therefore, CAVs could bring important social benefits to local communities [3] as they are suitable for a niche deployment on routes where expected passenger volumes are too low to be economically viable otherwise.

Building on our initial findings regarding CAV route optimisation [9] and subsequent feedback from transport policy officers, in the present study, we demonstrate an effective way of combining macro-level mobility simulations with multi-objective evolutionary algorithms (MOEAs) [6] to discover realistic optimal trade-offs related to CAV-serviced PT routes.

2 Proposed Approach

Several graph-based data-driven techniques for simulating (at a macro level) the reachability provided by multi-modal transport systems have been proposed over the years [11, 10, 5]. As we aim to use PT accessibility assessments to inform fitness computations within MOEAs, simulation speed is highly critical and we developed a bespoke lightweight spatial-temporal modelling solution that delivers substantial efficiency by enabling the independent modelling of the static (i.e., roads, pathways, existing PT routes) and transient (i.e., candidate CAV route) parts of the PT network graph. Furthermore, our macro-mobility simulation is based on a reversible graph structure that facilitates the computation of both inbound and outbound reachability (isochrones) using Dijkstra's shortest path algorithm [8].

The abstract PT network graph used by our macro-level simulation is constructed by combining Open Street Maps (OSM) data sets (for road layout information) and General Transit Feed Specification (GTFS) files (for PT timetables). In instances where GPS coordinates do not line up exactly between the different data sources, small artificial edges are added to facilitate connections between OSM-based vertices and their nearest GTFS-based vertices.

For computing the average commuting time over a geographic area, we rely on a grid G of equidistant points with a spacing of 50m. For any grid point $g \in G$, $t_g(x)$ denotes the shortest multi-modal (baseline PT system, walking, new CAV service deployed on the route encoded in x) travel time to the target destination and is obtained by computing an inbound isochrone centred on the destination. Based on this, the optimal planning scenarios for CAV-serviced routes that we aim to investigate can be formally defined as multi-objective optimisation problems (MOOPs) that seek to:

$$\text{minimize } F(x) = (f_1(x), f_2(x), f_3(x))^T, \quad (1)$$

where $x \in [0, 1]^d$ is a real-valued encoding of the d possible stops that can be included on the route and:

- $f_1(x)$ is the **average commuting time** (in seconds) to the target destination across the entire geographic study area:

$$f_1(x) = \frac{1}{|G|} \sum_{g \in G} t_g(x) \tag{2}$$

- $f_2(x)$ indicates the **number of CAVs** required to operate the CAV service associated with route x and can be seen as a proxy for capital expenditure:

$$f_2(x) = n(x) \tag{3}$$

- $f_3(x)$ indicates the minimal road **route length** (in meters) required by the layout of route x and can be seen as a proxy for operating expenses:

$$f_3(x) = length(x) \tag{4}$$

It is important to note that the computation of $f_1(x)$ and $f_2(x)$ is based on characteristics of the CAV service associated with the route encoded in x. In order to define this service, we follow a 3-step process. Firstly, we create a list of the PT stops that will be serviced – i.e., all stops i for which $x_i \geq 0.5$. Secondly, the list of PT stops is sorted in a clockwise order based on the GPS coordinates of each stop[1]. Finally, a GTFS timetable of the new service is constructed subject to scenario constraints and parameters (e.g., operating times, desired frequency, travel speeds) and the number of vehicles required to deliver the service (i.e., $n(x)$) can be computed.

3 Exprimental Setup

Our real-life application scenario aims to support the West Yorkshire Combined Authority (WYCA) identify optimal routes for a CAV-centred approach to improve urban mobility in the North-West region of the Leeds Metropolitan Area (UK) illustrated in Figure 1. This region contains 10 districts, is serviced by 1,015 PT stops for local and regional busses, and includes three multi-modal PT hubs centred on key railway stations.

The left hand plot from Figure 1 indicates that the North of the region lacks high-frequency PT services. This is largely explained by a low population density that directly translates to reduced passenger volumes which in turn make high-frequency services unprofitable. Nevertheless, the presence of infrastructure (i.e., physical bus stops) is a strong argument for focusing our CAV-centred PT service case study on the northernmost district (i.e., Adel and Wharfedale). Another argument for singling out this area is that the current PT system was not explicitly designed to improve accessibility to other train stations apart from Leeds (Central) Station. By also providing easy access to the closest PT hub (i.e., Horsforth Station), a well-planned CAV-centred service could further stimulate low-carbon rail travel.

[1] The resulting order in which selected PT stops will be visited influences $length(x)$.

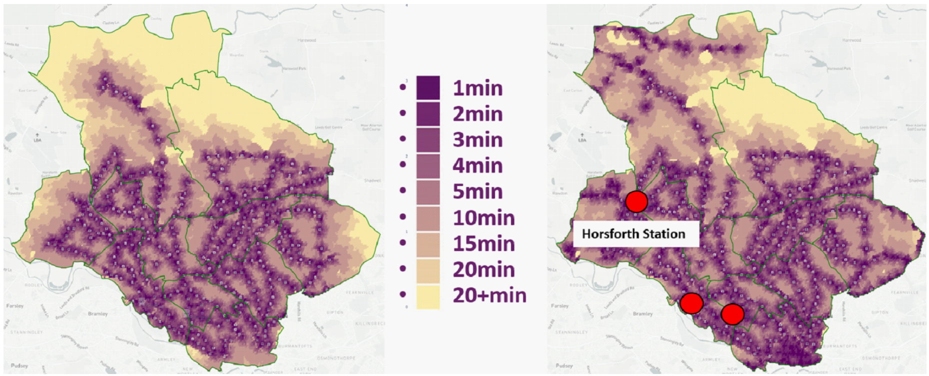


Fig. 1: Walking time to the 759 high-frequency PT stops (left) and to all 1,015 PT stops (right) in NW Leeds. Red marks indicate the 3 multi-modal PT hubs.

Based on feedback from WYCA domain experts, the new CAV-centred service should: improve the average commuting time to Leeds Central Station by the 10 AM on a workday (i.e., this is the target destination for $f_1(x)$), be bi-directional and circular and have a minimal frequency of one bus every 10 minutes[2], include Horsforth Station, operate between 06:00 AM and 07:00 PM. When carrying out the macro-level simulations, we assume an average CAV speed of 32 km/h, a 30 seconds PT stop waiting time and an average walking speed of 5 km/h.

By fixing these macro-simulation constraints and parameters we obtained an instance of the the MOOP defined in Equations 1 to 4 that aims to find subsets of the $d = 121$ PT stops in Adel and Wharfedale that can be optimally serviced (by different CAV fleet sizes and along road routes of different lengths) in order to improve average area-wise commuting time[3]. We applied the well-known NSGA-II [7] multi-objective solver on this problem instance using literature recommended settings and a population size of 200. We set a budget of 50,000 fitness evaluation / optimisation and we carried out 10 independent runs. Initial populations were randomly generated, but we opted for a 95% chance of initialising PT stops as not selected – i.e., $0 \leq x_i < 0.5, \forall 1 \leq i \leq 121$.

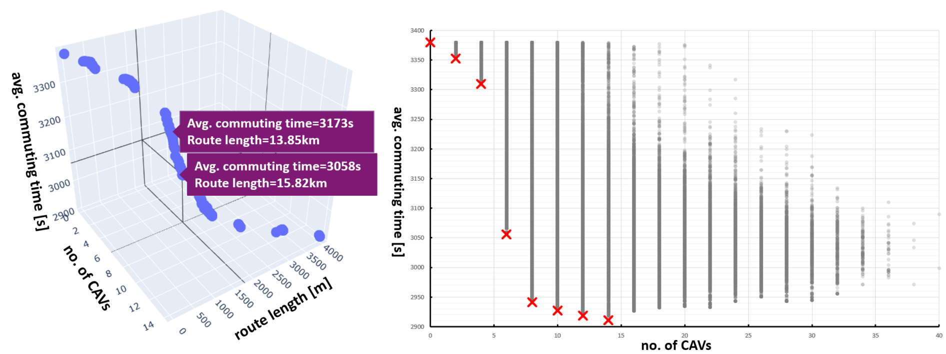
4 Results and Interpretation

In Figure 2a we present the Pareto front extracted from all the 500,000 candidate solutions explored during our experiments. While this result provides the most detailed view of existing trade-offs – e.g., the illustrated difference in average

[2] During service hours, across any consecutive PT stops A, B, C along the service route, one should not wait more than 10 mins. in B for a CAV to either A or C.

[3] The baseline to improve is $f_1(x) = 3379s$ and its associated isochrone is presented in the top left subplot of Figure 3.

commuting time and route length between two solutions that require $n(x) = 6$ CAVs –, the 2D Pareto projection from Figure 2b focusing on $f_1(x)$ vs. $f_2(x)$ trade-offs highlights much better three important insights: the used constraints result in services that always require an even number of vehicles, using more than 8 CAVs only brings marginal improvements in terms of average commuting time, and services that require more than 14 CAVs can't improve average commuting time at all.



(a) 3D Pareto front. (b) 2D Pareto front projection of $f_1(x)$ vs. $f_2(x)$.

Fig. 2: Aggregated multi-objective optimisation results.

The isochrone plots from Figure 3 focus on the 8 Pareto-optimal solutions from Figure 2b as they provide details regarding the best improvements in average commuting time that can be achieved when introducing CAV-centred PT services requiring $n(x) = 2$ to 14 vehicles. The associate route shapes are also displayed and they indicate that: (i) at least 6 CAVs are needed to link the main poorly connected area, (ii) 8 CAVs can efficiently connect all problematic areas, (iii) the usage of 12 to 14 CAVs leads to the generation of a feeder service for the existing high-frequency PT route in the area (marked by dark green in the top left baseline isochrone plot from Figure 3).

The subplots from Figure 4 illustrate the best solutions requiring 8 vehicles that were discovered by the presently proposed approach and by human planners[4] (i.e., domain experts). While the expert solution has the advantage that it also improves accessibility in the adjacent district, with respect to the study area, it is Pareto-dominated by the automatically generated result which delivers an improvement in average commuting time of $\approx 13\%$ (compared to $\approx 5.5\%$) whilst also featuring a shorter route length.

[4] Best out of 3 attempts.

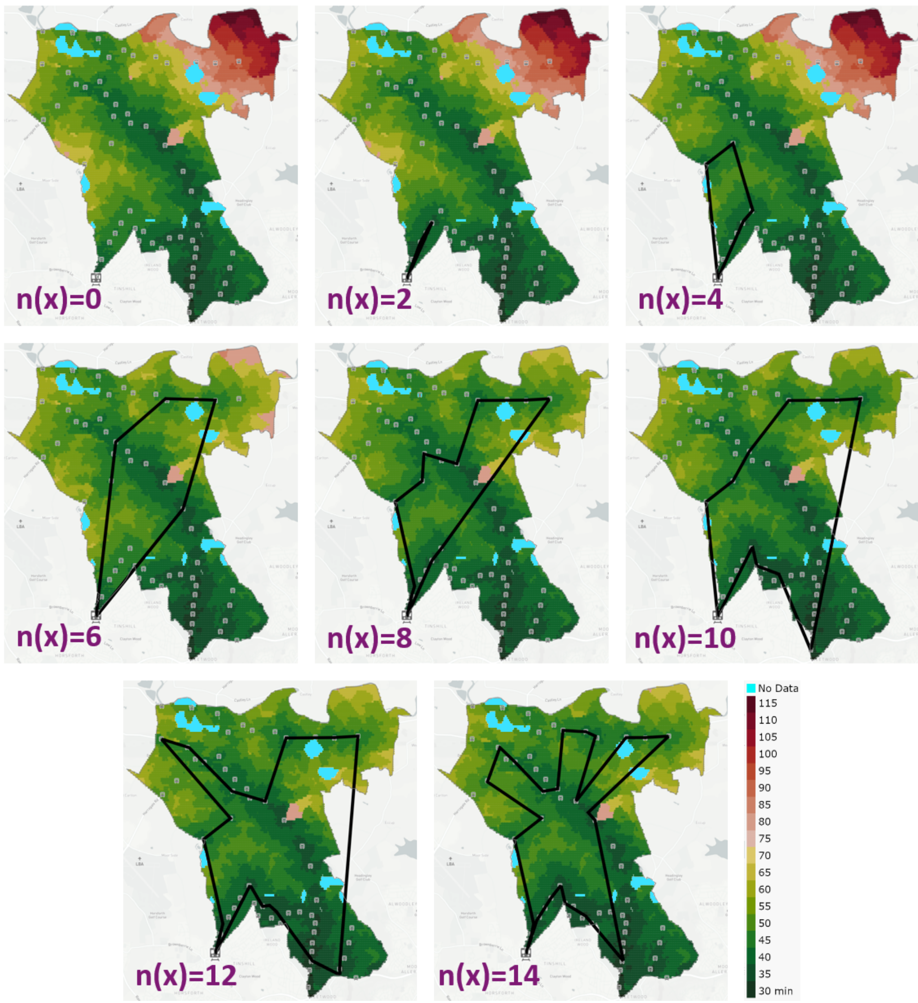
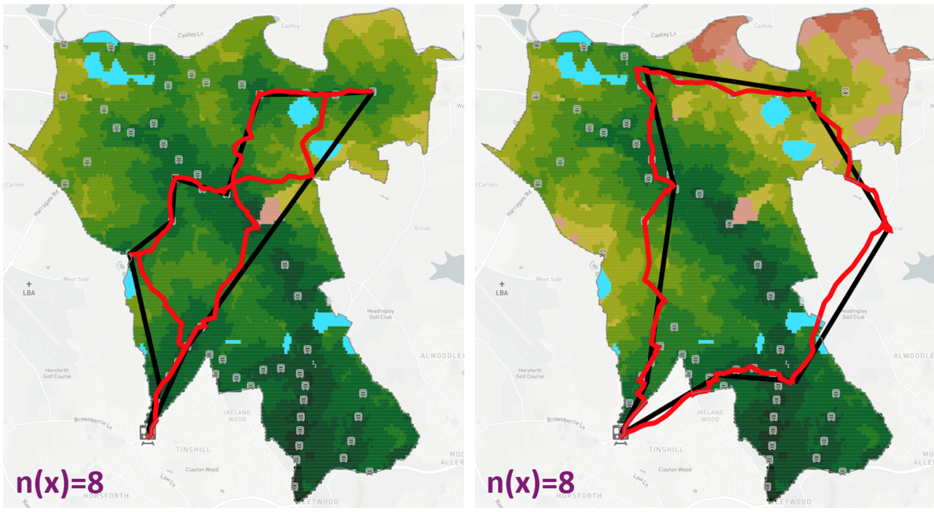


Fig. 3: Reachability isochrones of each $f_1(x)$ vs. $f_2(x)$ Pareto-optimal solution. The target of the commute is Leeds Central Station by 10 AM on a workday.

5 Conclusions and Future Work

In this paper, we have demonstrated an approach that combines multi-objective evolutionary algorithms and macro-level mobility simulations to support decision makers that wish to introduce a new route serviced by connected and autonomous vehicles (CAVs) to an existing public transport system (PT). Our approach facilitates the automatic discovery of optimal trade-offs related to improvements of the average commuting time across the analysed geographic area,



(a) NSGA-II: $f_1(x) = 2941s$ (b) Human planner: $f_1(x) = 3195s$

Fig. 4: Comparative routes (red=roads) and associated isochrones for the best solutions requiring $n(x) = 8$ CAVs.

investments required by the new route (i.e., capex), and cost associated with day-to-day route operation (i.e., opex).

As both the overall Pareto fronts and the individual routes we obtained have provided valuable insights to domain experts, we conclude that the proposed simulation↔optimisation strategy is a further step towards automating the production of realistic solutions that can tackle the increasingly complex challenges of public transport planning.

Moving forward, we plan to complement and refine our approach by investigating non-circular routes, experimenting with different route encodings and strategies for ordering selected PT stops, and improving our simulation assumptions using micro-mobility simulation results (e.g., obtained using the SUMO framework[1]).

Acknowledgments

The authors would like to acknowledge the support and constructive feedback provided by West Yorkshire Combined Authority transport policy officers.

This research was supported as part of ART-Forum, an Interreg project supported by the North Sea Programme of the European Regional Development Fund of the European Union.

References

1. Behrisch, M., Bieker, L., Erdmann, J., Krajzewicz, D.: SUMO–simulation of urban mobility: an overview. In: Proceedings of SIMUL 2011, The Third International Conference on Advances in System Simulation. ThinkMind (2011)
2. Bernhard, C., Oberfeld, D., Hoffmann, C., Weismüller, D., Hecht, H.: User acceptance of automated public transport: valence of an autonomous minibus experience. Transportation research part F: traffic psychology and behaviour 70, 109–123 (2020)
3. Borg, S.R., Lanng, D.B.: Automated busses to mobilize a suburb. In: The Royal Geographical Society (with IBG) Annual International Conference, Cardiff University (2018)
4. Brand, C., Anable, J., Tran, M.: Accelerating the transformation to a low carbon passenger transport system: The role of car purchase taxes, feebates, road taxes and scrappage incentives in the UK. Transportation Research Part A: Policy and Practice 49, 132–148 (2013)
5. Chondrogiannis, T., Nascimento, M.A., Bouros, P.: Relative reachability analysis as a tool for urban mobility planning: Position paper. In: Proceedings of the 12th ACM SIGSPATIAL International Workshop on Computational Transportation Science. pp. 1–4 (2019)
6. Coello Coello, C., Lamont, G., Van Veldhuisen, D.: Evolutionary Algorithms for Solving Multi-Objective Problems. Genetic and Evolutionary Computation Series, Springer (2007)
7. Deb, K., Pratap, A., Agarwal, S., Meyarivan, T.: A fast and elitist multiobjective genetic algorithm: NSGA-II. IEEE Transactions on Evolutionary Computation 6(2), 182–197 (2002)
8. Dijkstra, E.W.: A note on two problems in connexion with graphs. Numerische mathematik 1(1), 269–271 (1959)
9. Han, K., Christie, L.A., Zăvoianu, A.C., McCall, J.: Optimising the introduction of connected and autonomous vehicles in a public transport system using macro-level mobility simulations and evolutionary algorithms. In: Proceedings of the Genetic and Evolutionary Computation Conference Companion. pp. 315–316 (2021)
10. Innerebner, M., Böhlen, M., Gamper, J.: Isoga: a system for geographical reachability analysis. In: International Symposium on Web and Wireless Geographical Information Systems. pp. 180–189. Springer (2013)
11. Kirchler, D.: Efficient routing on multi-modal transportation networks. Ph.D. thesis, Ecole Polytechnique X (2013)
12. Mouratidis, K., Serrano, V.C.: Autonomous buses: Intentions to use, passenger experiences, and suggestions for improvement. Transportation research part F: traffic psychology and behaviour 76, 321–335 (2021)
13. Nakamura, K., Hayashi, Y.: Strategies and instruments for low-carbon urban transport: An international review on trends and effects. Transport Policy 29, 264–274 (2013)
14. Redman, L., Friman, M., Gärling, T., Hartig, T.: Quality attributes of public transport that attract car users: A research review. Transport policy 25, 119–127 (2013)
15. Van Lierop, D., Badami, M.G., El-Geneidy, A.M.: What influences satisfaction and loyalty in public transport? a review of the literature. Transport Reviews 38(1), 52–72 (2018)