Modular Autonomous Vehicles application in public transport networks: conceptual analysis on airport connection

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Abstract. Increased efficiency and optimized operation of transport networks represent two of the main topics of interest when discussing about modern road vehicles solutions. Taking steps towards more sustainable options, manufacturers of road vehicles are looking into advanced technologies that allow vehicles to run more efficiently and take advantage of all the available data on the road. When looking at the public transportation applications, trends point in the direction of using varied types of vehicles that can carry people around. The intermodality of these types of vehicles represents the most optimized way of travelling, combining the fast and secure characteristics of airplanes and trains, with the flexibility of last-mile options, such as taxis, buses, or trams. This paper discusses the aspects of implementing a MAV solution for the last-mile part of travel routes, connecting key points of a city, such as an airport or a train station, to other key locations of the city, such as city centre, important facilities, or marginal neighbourhoods.

1. Introduction

The rapid pace of technological evolution in recent decades made its mark in various industries, allowing for difficult solutions to become mainstream and easier to implement, leading to discoveries and improvements in all types of domains. As a downside of this worldwide spread of accessible solutions, pollution stands out as one of the most destructive consequences to the environment [1]. All industries that found themselves in a position of harming the environment by polluting, exploiting limited resources, or crowding certain locations, are acting on optimizing the way they operate, and, in the case of pollutions, reducing their carbon footprint into the atmosphere.

One of the main players interested in reducing carbon emissions is the transportation industry, the effects of which have been studied for decades. The World Health Organization classifies emissions coming from diesel-powered vehicles as carcinogen, following studies from 2010 [2] and 2012 [3]. As similar consequences are found for all fossil fuel-powered vehicles, the industry started to study the alternatives when it comes to powertrains solutions, as battery electric vehicles, fuel cell vehicles, hydrogen vehicles come into picture [4, 5]. As optimization is key when talking about reducing the negative effects on the planet, developments of automated systems that allow assisted and autonomous driving offer solutions in reducing operating costs of commercial and passenger vehicles, minimizing energy consumption of all sorts, and offering a safer and more reliable way of transportation.

Benefits of similar automated systems are to be found in domains that use them for a longer period of time, such as aeronautics and railroad industries. Here, human intervention has been reduced or removed completely from controlling airplanes, trains, and subways, resulting in safer exploitation of the equipment, increasing the lifecycle, and reducing operational costs.

In the direction of evolving these automated systems, the Society of Automotive Engineers (SAE) defines six specific levels of driving automation that a vehicle can achieve, based on features and functions that it can offer. The first three levels (SAE Level 0 – SAE Level 2) implies that the driver is still responsible for all driving duties and the vehicle does not present self driving capabilities. In these levels, driver support features are present, such as automatic emergency braking (SAE Level 0), adaptive cruise control (SAE Level 1) and adaptive cruise control together with lane centering (SAE Level 2). The next three levels (SAE Level 3 – SAE Level 5) describe self–driving vehicles. Driver interventions are expected only for SAE Level 3, as vehicles in this class are intended to serve as traffic jam chauffeurs, while at higher speeds, the automated systems are not fully operational. SAE Level 4 and SAE Level 5 applications represent vehicles that can drive autonomously, e.g., local driverless taxis. The difference between the two levels is that the latter can drive the vehicle under all conditions, whereas the other one can operate safely under limited conditions [6].

In applications of passenger transportation, such as public transport networks, autonomous vehicles (AVs) of various kinds are starting to make their appearance [7, 8, 9]. Ranging from small shuttles with reduced carrying capacity, such as the units implemented in the Horizon Europe ULTIMO project [10], to full-sized buses, like the specimen presented by CAVForth, in Scotland this year [11]. As the need for autonomous vehicles with the sole purpose of transporting passengers exists in various locations, with or without the optimal conditions to operate such vehicles, the more popular solutions that are adopted and implemented for public use are represented by the shuttle buses. Being smaller in dimension, with limited carrying capacity of up to 15 persons, applications are often found to be in restrained areas and controlled environments with less traffic, such as campuses, industrial areas, and airports. In 2020, upon a comprehensive review of autonomous shuttle buses as a solution for public transport, C. Iclodean presents the active fleets of autonomous shuttle buses all over the world, summing up to 55 applications [12].

Progressing from the concept of autonomous vehicles, several applications in public transport networks can greatly benefit from the implementation of modular autonomous vehicles (MAVs), similar to other domains that already use such concepts: farming, freight transportation and warehouses. By combining the power and capacity of multiple autonomous vehicles in shuttle configurations, it is possible to form a train of vehicles that execute the same transportation task, run on the same route, until each of the modules breaks apart the connection to the leader and starts performing its own transportation task on a different route. In such a way, a fleet of limited number of vehicles can cover a larger pool of requests for different routes. Each vehicle can be treated as a module in a connected fleet, which, if managed in a proper manner, can optimize the operation tasks with the purpose of reducing waiting times for the passengers, taking care of all driving related tasks in order to obtain a safer trip and using the available energy in the most optimized way possible.

Modular autonomous vehicles represent a current sustainable transport solution that has the potential to revolutionize local public transport networks, especially airport connections. The main advantages of the MAV compared to the classic transport system are the energy efficiency, the comfort and safety of the passengers, the reliability of the vehicles, the flexibility of the reconfiguration of the routes and the operating schedule, respectively the possibilities of integrating any public people transport network.

Another important aspect resulting from the integration of MAV into a public passenger transport system is the research and development side for the concept of Autonomous Driving, especially due to feedback from a large target group of people, the possibility of operating on mixed routes (airport – closed circuit, urban routes – roads open to public traffic), respectively their integration into various IT platforms for ticketing and GPS tracking that serve public people transport.

Correlated with European and international legislation regarding the implementation of autonomous vehicles on roads open to public traffic [13], before testing the operation of an autonomous vehicle in real conditions, it is necessary to carry out simulations on a virtual model of this vehicle, covering real application scenarios in a virtual environment similar to the real environment, highlighting any possible deviations from real scenarios ("The manufacturer of the autonomous vehicle must evaluate the functional safety of the autonomous driving system using a number of test scenarios that include false negative and false positive ones. Simulation method may be used, subject to their validation the approval authorities/technical services in accordance with the procedure for virtual testing in Directive 2007/46/EC or Regulation 858/2018.").

Hence the need to develop virtual models of autonomous MAV vehicles, configured based on the real characteristics of the main shuttle bus models spread across Europe: Navya, EasyMile, Auve Tech, 2GetThere, e.Go, etc.

Using advanced scheduling and optimization methods, a carefully developed management system can take into account all types of aspects, from available energy for each module and route requests to traffic jams and other hazardous events. By using intelligent algorithms and accessing data over a large period of time (e.g., one year, in order to cover all possibilities of transport requests, crowded seasons and hazards) an advanced system can predict the necessary capacities and ensure all modules are ready from all perspectives to act accordingly and complete the tasks without or with limited human intervention. Such systems may also track the usage and wear of each module and schedule any mandatory or needed service work and inspections.

To analyze the benefits of implementing an MAV fleet in an existing public transport network, a specific case is taken into consideration: the public transport routes from the city of Cluj-Napoca, Romania, linking key locations of the city to the "Avram Iancu" Cluj International Airport. These locations represent extremities of the urban area, such as the southern end of the city and the western end, which locates itself in the opposite direction of the airport, located in the eastern part of Cluj-Napoca, as well as a high interest area: the bus terminal. These specific routes are picked due to their demand and capability to serve as an important component of the intermodality concept, having the role of the last-mile personal transport. In this idea, a person coming into the city via airplane or train (considering the train stop near the airport terminal), can use the public transport to reach their destination, either that being a bus terminal which connects the metropolitan area or other small cities nearby, or being an accommodation in one of the main neighborhoods of the city. This proposed solution may be put into use in a non-stop operating schedule, or only at night, when the conventional public transport routes are limited to just a small number. The second option is also benefiting the limitations of autonomous systems of SAE Level 4, which thrive in a less crowded environment with controlled routes.

2. Current solution

The requests for transport tasks and covering of the routes is directly linked to the population, people flow through the airport and key places of the city, events and more. As an overview of the situation, the below table presents some of the relevant factors defining the needs taken into consideration when developing a public transport network.

Table 1. Public transport network overview [14]

Parameter	Value
Population	286.598
Number of travellers using public transport (annually)	76.918
Number of available routes	55
Number of bus stops	305
Number of available buses	246

Looking at the current solution that is implemented in the public transport network, the linkage between the bus terminal, which is located north from the city center, is done by a combination of two bus routes during the day, which continue further to other parts of the city, as presented in the below two figures.

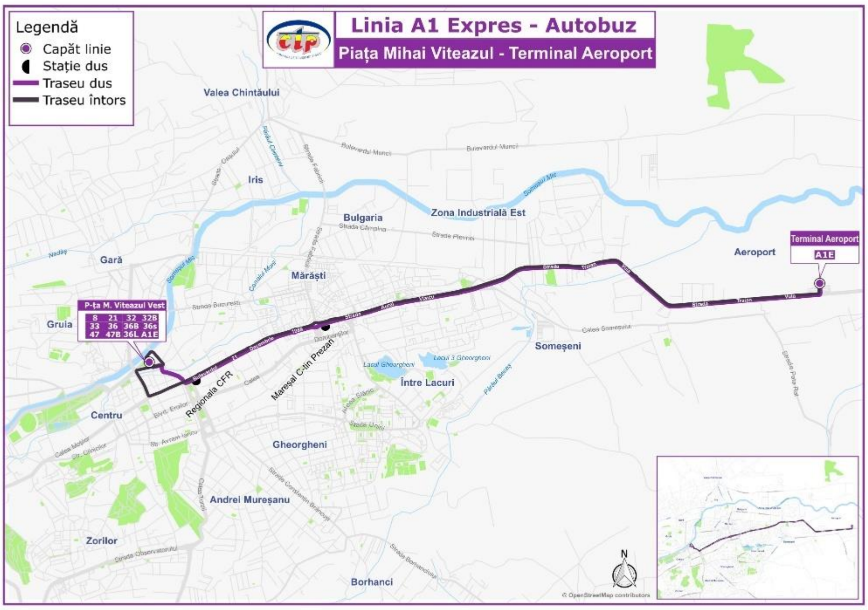

Figure 1. Route from Airport to Cluj-Napoca city centre [14]

Figure 2. Route from Cluj-Napoca city centre to Bus Terminal [14]

Although, during the nighttime, these routes are limited and connections from the airport to the bus terminal are made with full-sized buses, which often travel more than half-empty through their entire route. In this application, the energy consumption is compromised, in order to honor regular routes.

The current planned route that links the airport to the most western part of the city, passing through city center and multiple neighborhoods is done in this case also, by combining the connection from the airport to the city center, together with the below illustrated bus line.

Figure 3. Route from Cluj-Napoca city centre to Western area of the city [14]

While still going halfway through the city center, the routes connecting the airport to the southern neighborhoods steer away from the most crowded areas and experience smaller requests than those who lead to West, where a near locality with 52.735 inhabitants lies. Although the southern area of the city leads to important objectives in the metropolitan area, such as industrial parks (Turda, Câmpia Turzii), the public transport routes do not reach those places, as they are further than 30 km from the city. These routes are presented below.

Figure 4. Route from Cluj-Napoca city centre to Southern area of the city [14]

Studying the available data leads to the conclusion that not all routes are optimized in a meaningful way, often having the same outcome: buses travel more than half empty to end of lines in order to satisfy a reduced request from the travelers. With the scope of reducing the time buses are riding at less than

50% capacity, a feasible solution that allows modifying the configuration of the vehicles is to be studied. The main application that can satisfy these criteria is implementation of modular vehicles along all specified routes.

3. MAV solution

In order to present the modular autonomous vehicles implementation in a more accessible approach, the routes of the existing public transport network presented in the previous chapter are broken down into relevant segments, which correspond to parts of the course on which the modules (i.e. individual autonomous shuttles) are riding together, connected to one another, and parts which are covered by one ore more vehicles, disconnected from the main train of vehicles.

For this scenario, three separate classes are considered:

- ABT – modules that ride from the airport to the bus terminal, in the Northern vicinity of the city center;
- ASC – modules that ride from the airport to the Southern area of the city, passing through some of the main neighborhoods;
- AWC - modules that ride from the airport to the Western area of the city, passing through different main neighborhoods than the ones ASC is passing through.

By picking only these three routes, the majority of main neighborhoods, which are the oldest, most developed, and populated ones, are covered in one way or another. This does not mean that the presented connections satisfy all the transport requests in these locations, as there is a large area to cover, making it virtually impossible to do so by using only three routes.

As the airport is situated in this case on the outside of the city, near the Eastern border of the urban area, the marked route in the below Figure shows the starting point for all routes, which is the International Airport bus terminal (marked as “Airport”).

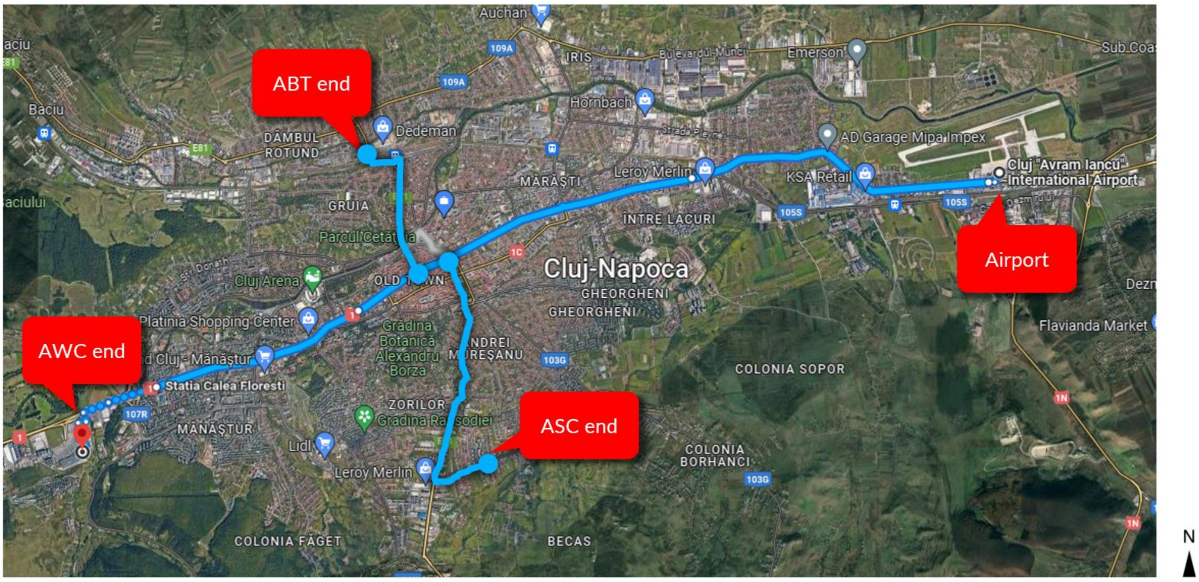

Figure 5. Planned routes for MAV solution simulation

The ends of each line or route are highlighted in the same figure as follows:

- **ABT** end – End of the line for route **A**irport to **B**us **T**erminal;
- **ASC** end – End of the line for route **A**irport to **S**outhern Area of **C**luj;
- **AWC** end – End of the line for route **A**irport to **W**estern Area of **C**luj.

The above-mentioned modules are considered to be designed in such fashion, that they are allowing to physically connect to each other and form a train of vehicles, with the modules that detach last from the formation leading the pack. Note that each designated module, like AWC, ASC or ABT, is presented as a singular unit here, for simplification. Depending on the circumstances, the module might be formed by multiple units, leading to an increased capacity for each individual route. The below figure illustrates the vehicle train order, as the modules ride together until one of them needs to detach and follow their own designated route.

Figure 6. Illustration of a road train of vehicles

Along the route, there are so called "detaching points", where modules disconnect from the pack and start operating on their own. These locations might differ over time, depending on various hazards, events, traffic jams or restrictions and are not necessarily the same as "attaching points" – which are to be considered the locations on the map where these modules come back together and form a pack traveling to the International Airport bus terminal. It is not mandatory that the same modules must pair on the return routes, as segments that they cover are not the same length or do not have the same duration of travel. In addition, on the return route there might be less restrictions or less requests of passenger capacity, leading to suboptimal operation of the fleet, if the total capacity of the modules train is similar to the cases of conventional buses, less than 50%.

Detaching points are noted on the map shown below, as "ABT out" and "ASC out". There is no "AWC out" point in this case, as the AWC module are leading the formation and continue their journey to the end of the line – AWC end.

Figure 7. Detaching points for each module

The order of attaching and detaching of the train module, for exemplification purposes, considers the AWC component as a leading module. The below table shows the progress of each module while covering their respective routes and fully executing each task.

Table 2. MAV train configuration along the routes

Start End	A[1] ASC out	ASC out ABT out	ASC out ASC end	ABT out AWC end	ABT out ABT end
AWC	L[2]	L		L	
ABT					L
ASC			L		

[1]International Airport. [2]Formation leader.

To expand on the concept definition and obtain data for studying the differences between conventional way of transportation and MAV solution, IPG CarMaker is used to model and simulate the public transportation tasks that need to be executed in order to cover the specified routes.

IPG CarMaker is a simulation software, developed by IPG Automotive GmbH, used in the industry as a support application for developing and testing automobiles and light-duty vehicles. Throughout the catalog, some solutions offered by IPG are fitting with this paper’s direction of analysis – autonomous vehicles. Being an open platform, it allows to be integrated into other software, leading to complex data acquisition and processing, as well as advanced modeling of vehicles, traffic characteristics and driving courses.

Based on available market solutions such as EasyMile EZ10 or Navya Arma autonomous shuttle buses, a module is defined in CarMaker as an AV with the maximum capacity of 900 kg (approximately 12 person). Road trains containing more modular vehicles are then defined by putting modules together. Defining parameters of the modules are added up to obtain the specification list of the train, holding two or four modules together.

By acquiring relevant information (distance, trajectories, elevation etc.) in GPX (GPS Exchange Format) and KML (Keyhole Markup Language) files, of the routes linking the city with the airport, accurate representations of the courses can be loaded up in the CarMaker software. On these courses, specific maneuvers are defined (e.g., driving on the first lane, not cutting corners), as well as driving behavior regarding speed regulation and accelerations (e.g., rapid acceleration until reaching the velocity thresholds, tolerances around the target traveling speed). Using these details, transport solutions can be configured precisely to fit the needs of individual routes.

For simulating purposes, a conventional electric bus is considered as the conventional solution. This is then compared to the proposed MAV solution. From the modeling perspective, the electric bus is considered to be approximately the same weight and capacity as a road train containing four separate modules. For each of the two solutions, simulations are made on each defined segment of road, with equally distributed passenger load of 900 kg per module (front, center, rear of each module), at the start of the simulation scenarios. Traffic characteristics are not considered, only road specific variables, such as elevation changes and curves. By following the algorithm of pairing and unpairing the modules defined in Table 2, passenger loads, total mass and powertrain-specific parameters are altered on each disconnection of modules, simulating people getting in and out of the vehicle.

Using the conventional solution simulation results as the benchmark, the outcome of the modular autonomous vehicles simulations shows significant improvement in overall battery management efficiency. As multiple electric buses are needed in order to cover multiple routes whitin the urban area, the cummulative energy consumption of those buses exceeds the total consumption of all the modules used in the MAV setup. Eventhough the electric buses are not riding at full passenger loading capacity, the energy consumption differences between a half-empty bus and a full-loaded bus do not match the energy consumption of a road vehicle train. Starting from 85% state-of-charge (SoC) for both test cases, the below figure shows a comparison between final state-of-charge of the vehicles, after transportation task execution, for Bus (conventional solution) and MAV (proposed solution).

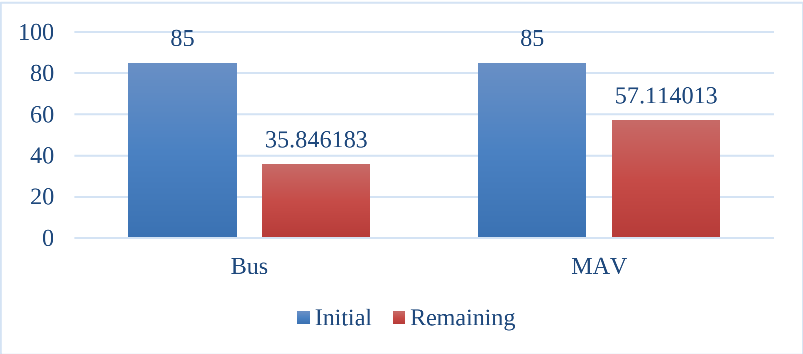

Figure 8. State-of-Charge comparison chart

The results point to a significant improvement of the remaining state of charge, measuring 59% more energy stored in the MAV battery pack, while carrying the same number of passengers, in the same road conditions. The considered routes extend on a distance of 14.2 km (from the International Airport to the most western area of Cluj-Napoca) and another of 10.5 km.

To be noted that, the models used in the simulations are not validated with available open market solutions and their sole purpose is to indicate the direction in which study must continue. The concept needs to be proven right for such applications, before starting to invest more resources and analyze in more detail all the real-life limitations.

4. Discussion

As a first step in tackling the issue of public transport network optimization and implementation of green solutions that lead to a more sustainable transportation in the future, the electrification of the bus fleets is the way to go. Even though costs of starting and maintaining such applications is high, the local pollution is demonstrated to be reduced in the case of the same city, Cluj-Napoca, by 668.45 tons of CO_2 and 5.618 tons of NO_x each year [15].

Moving forward within this trend and following the latest and most advanced solutions on the market, the autonomous shuttles, especially in a modified form of modular autonomous vehicles, show a feasible solution for an existing network, in an old city with narrow streets and existing infrastructure that presents limited possibilities of expanding and highly expensive options to repurpose urban areas and streets.

As the autonomous vehicles trends are expanding, even more manufacturers, researchers and officials turn their attention to this domain [16]. Legal framework, although sometimes not existing or existing in a very limited form, starts to show recognition, understands the necessity of such applications, and moves forward with creating laws, regulations and specifications that allow others to research and develop with the scope of obtaining safer, more cost efficient and optimized road networks.

Considering the concept of MAVs implemented in an existing transport network, for the case study of the city of Cluj-Napoca, Romania, there are clear advantages that suggest an implementation of such sort will lead to an optimal system that allows to reduce wear of the equipment, operational costs, energy consumption and improve the overall efficiency of the public transport network, while maintaining or reducing waiting times for the passengers and providing a safer environment for inhabitants of the city.

The disadvantages of this kind of application are the same worldwide: there are clear concerns about safety and reliability of the systems when interacting with populated areas, there are no clear legal framework put in place at the moment, as these solutions are starting to operate in limited areas. As the time advances and solutions become safer, more reliable, and adaptive, there is a certainty that an increasing number of cities, industrial areas, university, and sport campuses will benefit from the advantages of MAVs integration in existing solutions.

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