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# Flexible Capacity Road Passenger Transport: History, Current, Future

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**Abstract**
Regular passenger transportation plays an important role in the life of modern society. At the same time, the financial burden of paying for its operation falls on the state budget and is the subject of periodic measures aimed at reducing this budgetary burden. Implementation of such goals is usually carried out by reducing the number of flights, which leads to a decrease in the quality of passenger service and their outflow to the personal car, which leads to an increase in motorization with all the negative attributes inherent in this phenomenon.
This publication gives a literature review of scientific publications on the subject of the use of road passenger transport of dynamic capacity - trailer passenger vehicles, which in the period of growth of passenger traffic are coupled, increasing capacity, and in periods of decline - uncoupled, reducing capacity. Modern scientific and practical tendencies of this direction abroad are shown. A new approach to the organization of regular passenger transport operation in the Republic of Belarus is proposed, which consists in the daily forecasting of passenger capacity for each trip of each route with the subsequent assignment of passenger vehicles of flexible capacity to such trips, maximally corresponding to the available passenger capacity.

**Keywords:** Public Transport, Flexible Capacity, Efficiency, Passenger, Transportation Operator

## 1. Background

Flexible Capacity Road Passenger Transport (FCRPT) started with the use of trailed passenger vehicles (trailers, semi-trailers) to flexibly respond to fluctuations in passenger traffic, increase capacity and reduce the number of drivers started more than 100 years ago [1]. The first bus with a trailer was developed in the 1920s in Amsterdam [2]. During World War II and the first post-war years, trailer buses were used as a simple and economical method of bus transportation to replace worn-out conventional bus fleets. The semi-trailer buses were simple and inconvenient, but each could carry more passengers than a single bus and almost as many as a double-decker bus, which at the same time did not have the disadvantages inherent in the latter - increased passenger boarding and alighting time with high passenger occupancy. Trailer passenger vehicles were also operated in India [3], Lausanne [4], Australia, Mexico, and the USA [1].
The territory of the former USSR was no exception. In 1966, the Kiev engineer V. F. Veklich, in order to solve the problems of driver shortage, increase the profitability of transportation and the availability of routes with extremely high passenger traffic, created a system of connecting trolleybuses into a train (Fig 1) with control by a system of many units, which is a method of controlling railway rolling stock, in which several locomotives or motor cars are coupled into one train, and the traction engines are controlled from one control station and one locomotive crew.

**Fig 1:** Trial operation of the world's first trolleybus train of two MTB-82 trolleybuses [5]

Veklich's proposed coupling system (Fig 2) allowed trolleybus trains to be uncoupled in 3-5 minutes right on the route between the morning and evening rush hours. After uncoupling, the driver of the train continued on the first trolleybus train, and the driver of the following train transferred to the second trolleybus train. The released train remained on the route for idling or went to the depot for preventive maintenance.


**Fig 2:** Coupling device of trolleybus train ZiU-682G [6]

In order to create trolleybuses capable of operating in such control modes, Veklich V.F. carried out a great deal of work to solve the following scientific and technical problems: Justification of parameters of coupling and control devices, development of control systems for braking of slave train links, development of methods and means of diagnostics of special train equipment and other technical tasks. As a result, both on the leading and the slave machines synchronously worked engines and brakes, they had no problems with lack of traction, skidding and slipping, and they were controlled by one driver from the cab of the front machine. The capacity of one unit of release was doubled, which allowed to reduce the number of drivers, and a special turning and coupling device provided movement of the slave machine on the track of the leading machine.
The author shows that the actual economic effect from the introduction of trolleybus trains amounted to 2.1-4.9 thousand rubles per train per year [7, p. 29]. It is also shown that for one route the cost reduction reaches 13974 rubles per month (by 25%) [8, Table 4]. In addition, the author has established [7, 8, 9] that:

- The use of such trolleybuses, compared to articulated units, have higher braking and dynamic characteristics, as well as capacity;
- Safety during transportation by such trolleybuses is 2.6 times higher [7, p. 30];
- The use of trolleybus trains makes it possible to increase the average daily duration of the driver's shift and reduce the required number of drivers.

Separately, it should be noted that such trolleybus trains were operated illegally until 1976, although there were more than 160 units in Kiev alone. Only the absence of traffic accidents due to the fault of their design did not create problems. Before their operation it was necessary to conduct acceptance tests and develop appropriate specifications, which was not done, because the USSR State Automobile Inspectorate could not decide on an organization that could be entrusted with this non-standard task - after all, there was no experience of testing non-rail trains in the USSR. Only in 1975 it was authorized to do so by the State Automobile Inspectorate of the Ukrainian SSR. With the introduction of the TU "Trolleybus train" [10] on March 31, 1976 the trains were legalized.
It should be noted that the proposals given in [7, 9, 8] did not concern the technology of organization of transportation with the use of trailed trolleybuses, i.e. the methodology of distribution of these trolleybuses by routes, by hours of the day, etc. is not described, which nowadays, taking into account the digitalization of the transport industry, represents a promising vast field of activity to improve the efficiency of urban regular passenger transport.
Trolleybus trains were operated in many cities of the former USSR. The last train was decommissioned in 2013 in Krasnodar [11].
The main reasons for the abandonment of trailed passenger vehicles were:

- The need to have a conductor in the trailer;
- Inability to fit into narrow city streets;
- Uncomfortable traffic conditions for passengers in the trailer unit;
- Lack of low-floor trailers;
- Lack of heating in the trailer;
- Impossibility to control the order in the trailer by the driver.

## 2. Current status of the DPTPA – везде поменять аббревиатуру

Two conceptually different types of vehicles are currently represented by DPTDVs:

- Trailer passenger vehicles, known in the literature as maxi-Train, BusTrain, trailer bus, Buszug, Busanhänger, Anhänger Bus, pessenger bus trailer;
- Modular passenger vehicles, known in the literature as modular autonomous buses (MAB); modular autonomous vehicles (MAV); modular bus units (MBU); Dynamic Autonomous Road Transit (DART); modular, adaptive, and autonomous transit system (MAATS)).

*Trailer passenger vehicles*

Nowadays, buses with trailer under various names are operated in:

- Germany. In Munich (Fig 3), 10 pairs of buses with semi-trailers were purchased in 2017 at a total cost of €4.9 million [12], as well as in Osnabrück, Siegen, Konstanz and Reutlingen [13], Hanau, Gröbenzell, Zusmarshausen, Grafenberg, Erlensee, Altenstadt [14] and many other German cities [15]. In Germany, since 2003, the legislation allows the transportation of passengers in special trailers, provided that a special permit for this mode of transportation is obtained;

**Fig 3:** Buses with trailer in Munich [12]

- Graz, Austria [16];
- Netherlands [17].

Bus trailers are currently produced by:

- HESS company (Switzerland) (Fig 4);

**Fig 4:** HESS buses [18]

- Sono motors, Germany (Fig 5);
- MAN Truck & Bus GmbH (Fig 6);
- Göppel Bus GmbH, Germany (Fig 7).

Since March 2023, the research project "MINGA" has been funded [22], budget 13 million euros, which provides for the implementation of platooning of buses (platooning), which consists of buses following each other at a short distance and articulated by a virtual drawbar.

Unfortunately, the author of this publication could not find any scientific articles describing (justifying) the technologies of organizing passenger transport consisting of trailed passenger vehicles.


**Fig 5:** -Sono Motors buses [19]

**Fig 6:** MAN buses [20]


**Fig 7:** GO4CITY10 (G56) bus with GO4CITYT (G13) trailer of Göppel Bus GmbH (Germany) [21]

*Modular passenger vehicles*

In general, the evolution of passenger transportation technologies is well described in [23]. According to this description, modular passenger vehicles are currently the most modern stage of passenger transportation.

The pioneers in the development of modular passenger transportation are NEXT, Dubai [24]. NEXT is an advanced intelligent transportation system based on multiple modular electric vehicles (Fig 8). Each module can attach and detach from other modules on standard urban roads. When connected, they create a bus-like open area between modules, allowing passengers to stand and move from one module to another.

**Fig 8:** Modules of the NEXT system [24]

Module sales are scheduled for August 2024. Capacity of the module is 15 passengers (5 seated and 10 standing), driver control. The cost of purchase of one module from 1950 Euro per month. Payment within 60 months, ie the cost of one module with a capacity of 15 passengers from 117000 euros. The length of one module is 3,28 m, i.e. in accordance with the current Rules of the Road Traffic of the Republic of Belarus a maximum of 5 modules can be coupled. The total capacity of the coupling will be 75 passengers, and its cost from 585000 euros [25].

The possibility of using modular passenger vehicles (Fig 9) in urban transportation was also considered in Singapore in the framework of the study and evaluation of Dynamic Autonomous Road Transit (DART).

**Fig 9:** Singapore's dynamic autonomous road transportation [26]

Possible variants of the technology of organizing the work of such modules are widely enough covered in scientific literature. For example, in [27] such technology is illustrated by the figure (Fig 10).

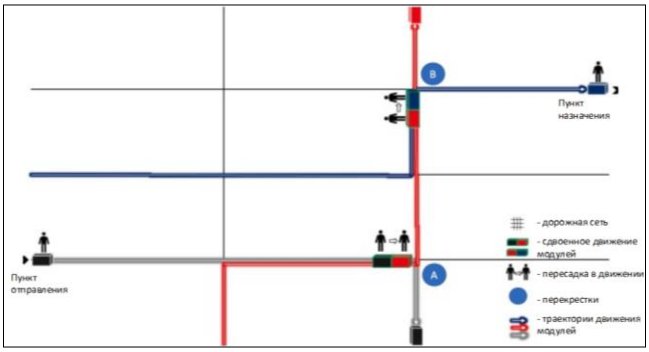


**Fig 10:** Illustrative example of a passenger journey in the proposed modular bus system [27, p 82]

It is assumed that passengers book a trip via a mobile application and specify their departure and destination points. The system then generates an optimal route for each passenger and assigns a module to operate on the route. In the on-move transfer zone, passengers can transfer between modules on the move to reach their destination (Fig 11). This reduces travel time and increases module utilization efficiency.

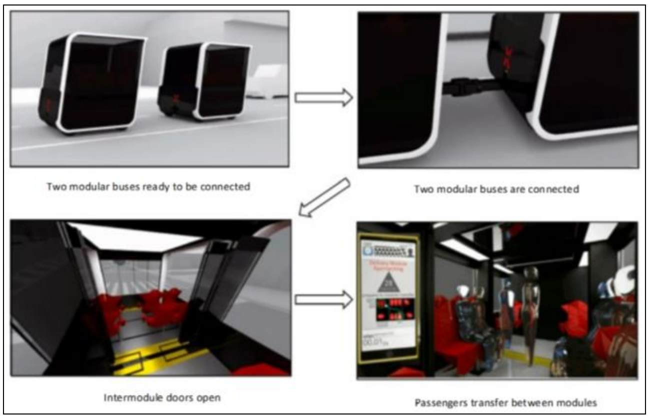


**Fig 11:** Illustrative example of a passenger journey in the proposed modular bus system [27, p 85]

The paper notes that modular passenger transport does not have fixed routes and schedules, but instead uses an adaptive strategy that allows it to change its routes in real time depending on the needs of passengers. The example calculation on arbitrary input data given by the authors showed that under the traditional system of using conventional buses, the average travel time is 17.09 minutes, while under the proposed MAATS system it is 14.7 minutes, i.e. the average travel time is reduced by 18%.

In [28], the possibility of using autonomous modular buses to improve urban public transportation and passenger comfort is investigated. The author considers 4 types of services in the study:

1. **Conventional bus service (S1):** Buses make stops according to the established schedule and route, and passengers get on and off the bus at stops according to their needs. This type of service is the baseline scenario for comparison with other types of services considered by the author.
2. **Autonomous bus service (S2):** Similar to bus service (S1), except that the buses will be self-driven, without a driver.
3. **Wraparound Modular Bus Service (S3):** Is a concept aimed at minimizing passenger travel time to a level comparable to door-to-door service by eliminating the intermediate stops found in conventional bus service (Fig 12).

For this purpose, a bus stop concept different from the traditional bus stop has been developed. This concept places one or more autonomous modules (shown in green in Fig 12) at each bus stop, where users enter as they arrive to wait for a train consisting of autonomous modules of the same type (shown in green in Fig 12). When such a train arrives at a stop, it does not reduce its speed. At the same time, only those passengers who want to end their trip at the stop (shown in red in Fig 12) are disconnected from the train. To do this, they are grouped into the appropriate modules beforehand during the train's movement by transferring between modules through inter-module doors (see Fig 11). While the modules will slow down to stop, the reverse process takes place: The module(s) that were at the stop accelerate to join the train at the front. As a result of this operation, passengers (in the white pods in Fig 12) do not waste time at stops where they do not need to get off.

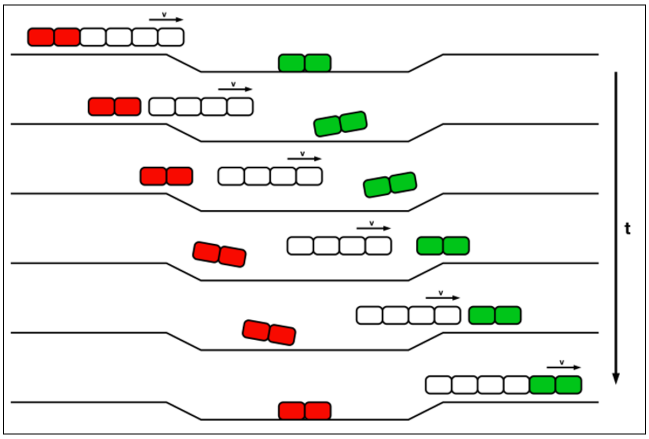


**Fig 12:** Image of the S3 service [28, p. 33]

Obviously, the S3 model, has operational advantages over the existing conventional model (S1), such as no driver labor costs, increased passenger delivery speed, which in turn reduces passenger delivery time and potentially reduces the number of vehicles in circulation. However, operation can be somewhat complicated and confusing as the modules need to be attached at the front of the modular bus and detached at the rear, and a certain inconvenience for passengers would be that they would have to move in motion from module to module. In order to solve these problems while maintaining the benefits of transferring along the route, the S4 service is proposed.

4 Service with modular buses based on the "mother" bus (S4) - modules are attached and detached only from the back of the mother bus (Fig 13). This operation means that, unlike the S3 service, this will use vehicles that physically travel the entire line at once, without stopping at intermediate stops (the mother bus is white in Fig 13). Such mother buses are conventional autonomous buses as in the S2 model.

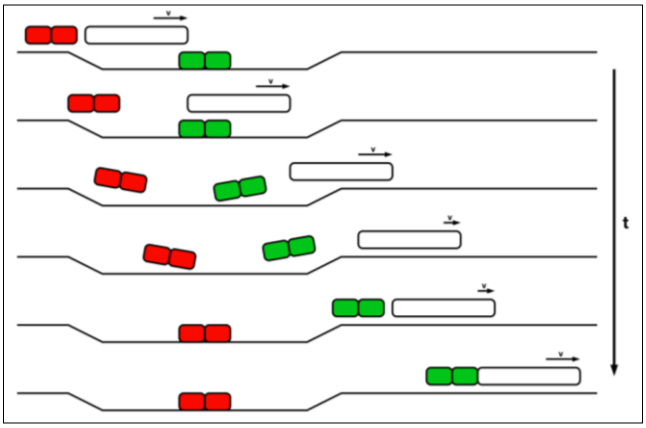


**Fig 13:** Scheme of service operation with modular buses based on the "mother" bus (S4) [28, p.44]

Thus, two types of vehicles coexist in this model: Autonomous high-capacity buses that do not stop at intermediate stops, and autonomous modules that hitch/unhitch from the back of buses and stop at intermediate stops. In all other aspects, the same assumptions will be adopted as in the S3 service.

Modeling of passenger transport operation under each of the four service options considered allowed the authors to highlight the areas of feasibility of each service. Thus, the change in the cost of system operation depending on the technical speed of movement is shown (Fig 14).

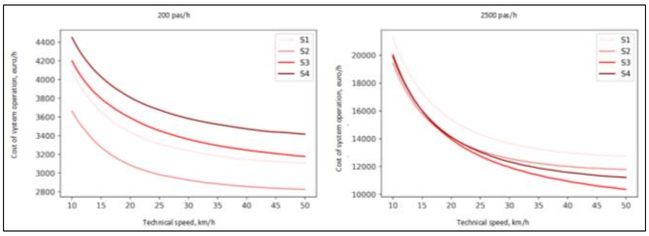


**Fig 14:** Cost of system operation depending on technical speed for passenger flow capacity of 200 and 2500 pass/h [28, p. 66]

Fig 14 shows that the S2 service is the most optimal for the whole analyzed speed range at low demand (200 pph). The high demand scenario (2500 pph) shows that the costs are clearly higher than for low passenger traffic. The S2 service is optimal for speeds up to 18 km/h. At higher speeds, the S3 service becomes the best.

Fig 15 shows the variation of operator costs (EUR/hour) and average passenger travel time as a function of technical speed. In general, the curves tend to decrease.

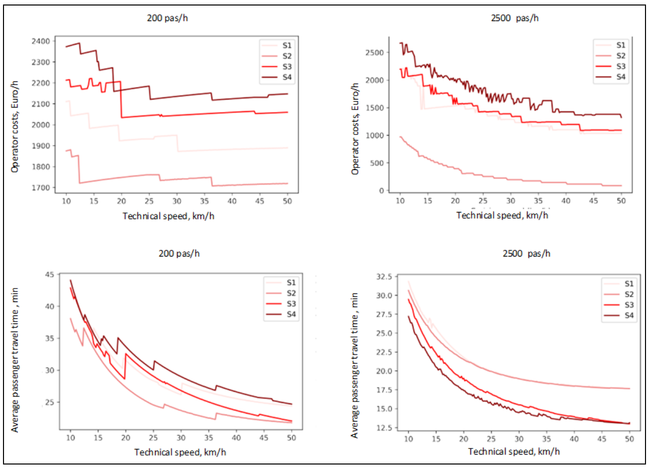


**Fig 15:** Operator costs and average passenger travel time depending on technical speed at passenger flow values of 200 pass/h and 2500 pass/h [28, p. 67]

As can be seen, the curves contain small jumps along their trajectory (see Fig 15). These jumps are caused by changes in the optimal values of both the travel interval and the distance between stops, which in turn cause significant changes in the costs incurred by the operator and the users. However, these jumps do not appear on nearly homogeneous curves representing system costs since they have opposite directions for the operator and for the users. I.e., for example, increasing the average distance between stops by 100 m may mean a reduction in the fleet required by the operator, but increases the approach and departure times of passengers. Therefore, they eventually level off and have no effect on the homogeneous trend of the system cost curve (Fig 15). This figure also shows that for all low passenger flow cases, the S2 service is preferred. This service will also be preferred for high passenger flow in terms of minimizing operator cost. From the point of view of minimizing travel time costs at high passenger flow at speeds up to 42 km/h, service S4 will be optimal. At higher speeds, the S3 and S4 services show approximately the same level of travel time.

The effect of passenger traffic on operator costs and average passenger travel time is also shown (Fig 16).

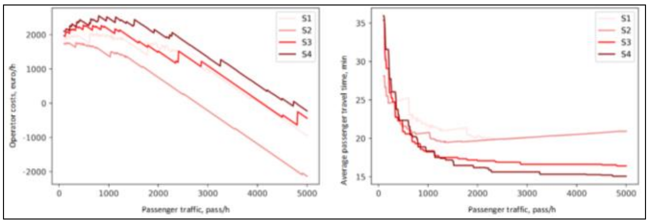


**Fig 16:** Operator costs and average travel time of users depending on passenger flow capacity [28, p. 69]

Fig 16 shows that from the point of view of reducing the operator's costs, the optimal strategy is S2. As for passenger time costs, at small passenger flow values (up to 750 pass/h) the optimal service will be S1, at passenger flow values of 750-1200 pass/h the optimal services will be S3 and S4. In case of further growth of passenger traffic the optimal service will be S4.

A graph of the sphere of expediency of application of the considered strategies depending on the capacity of passenger flow and technical speed has been constructed (Fig 17). As can be seen S2 is optimal below a certain threshold of demand, which decreases as the technical speed increases. On the other hand, service S4 is the most optimal at high demand (more than 3000 pass/h) and low technical speed (less than 20 km/h), and service S3 dominates the upper right part of the graph.

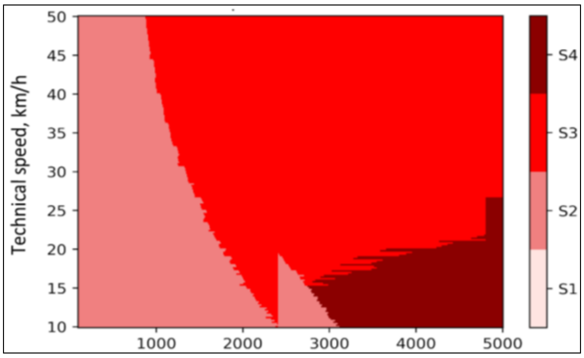


**Fig 17:** Optimal service depending on demand and technical speed [28, p. 71]

The spheres of feasibility of application of the considered services at different values of passenger traffic (1500 pass/h and 2500 pass/h), cost of autonomous passenger vehicle (from 0 to 1 million euros) and cost of module (as a fraction of the cost of autonomous vehicle) are given (Fig 18).

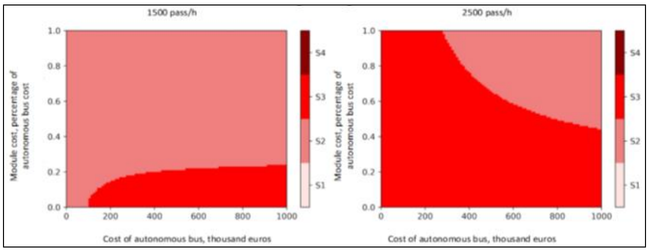


**Fig 18:** Optimal service depending on the purchase cost of autonomous bus and module [28, p. 73]

It can be seen that at a demand of 1500 pass/hour, the S3 service is most optimal when the purchase cost of autonomous buses exceeds 100000 euros and the module price is less than 20% of the cost of these buses, while S2 is optimal in the rest of the region (Fig 18). At a demand of 2500 pass/hour, the S3 service becomes optimal in a wider region: With the purchase cost of autonomous buses below 300000 euros and the module cost around 0.4, which makes sense since in high demand scenarios users have a greater weight on the total system cost and therefore a service that is more favorable to them becomes more optimal.

Similar conclusions about the feasibility of switching to autonomous passenger transportation are contained in other scientific publications, such as [29]. However, it should be understood that in the above calculations the authors used variables, the values of which will be significantly different for the conditions of the Republic of Belarus. For example:

- Cost of 1 passenger-hour - 12.5 euros [28, Table 2]. Calculated on the basis of an average salary of 2000 euros per month;
- Fare - 1 euro [28, Table 2];
- Purchase cost: regular bus 550000 euros, autonomous bus 650000 euros, module 150000 euros [28, table 3];
- Driver's salary including taxes 37.72 Euro/hour [28, Table 3].

Obviously, for the conditions of the Republic of Belarus the values of such initial data will be different, which casts doubt on the economic feasibility of the implementation of strategies S2, S3, S4. In addition, the implementation of strategies S3 and S4 provides for the movement of passengers inside the cabin during the movement of the vehicle, the skills of using a cell phone, which seems difficult to implement for some categories of passengers, including the elderly, as well as with luggage. Also, unmanned driving technologies of buses are imperfect and accidents involving them take place [30, 31].

Another bus system similar to the NEXT system is the DART system. The advantages of using such modular system buses are similar to the NEXT system described above, and are [32]:

- Better integration with the smart bus stop will provide a faster boarding/disembarkation process, which contributes to shorter bus dwell time;
- Dynamic road prioritization will provide smoother traffic flow with minimal negative impact on private vehicles;
- Demand-responsive dispatching function increases adaptability to demand fluctuations by adjusting the capacity of module trains to match passenger capacity;
- The platooning function ensures that the modules on the road at the same time are grouped into platoon(s), minimizing the traffic impact on roads.

Modeling of transport operation by the classical system and DART systems showed that the latter option is about 40% cheaper than the existing one [32, Figure 3].

In [33, Section 5.2], modular passenger vehicles are modeled using continuous simulation methods in one of the districts of Tampa (Florida, USA) in order to evaluate the efficiency of such a system compared to the existing bus system. The authors assume known abstract values of passenger traffic for the year 2040, equal intervals of passenger vehicles for both passenger service systems under consideration. Fig 19 shows the results of such modeling.

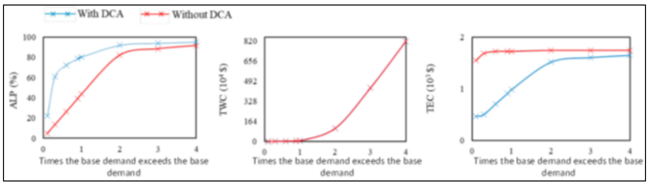


**Fig 19:** Performance indicators with and without modular passenger vehicles (DCA, dynamic train capacity adjustment) under different demand scenarios: ALP (average load percentage) - average passenger vehicle capacity utilization; TWC (total waiting cost) - total cost of passenger waiting time; TEC (total energy cost) - total energy cost of transportation [33, Figure 16].

It can be seen (Fig 19) that the use of modular passenger vehicles allows to increase the degree of capacity utilization and, as a consequence, to reduce the cost of energy required for transportation.

In [34], the operation of urban passenger transport is modeled using a single passenger vehicle, as well as a composition of modular passenger vehicles. The feasibility of using each of these methods is given (Fig 20).

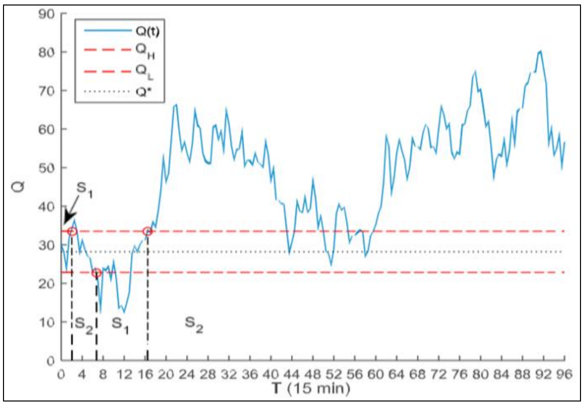


**Fig 20:** Scope of feasibility of a single bus and a modular bus lineup [34, p. 397]: Q(t) - density of demand at time t (trips / square mile per hour), $QH$ - upper boundary of demand at which it is reasonable to switch to modular passenger vehicles, $QL$ - lower boundary of demand at which it is reasonable to switch to single bus service; S1 - strategy of operation by single buses with a capacity of 10 passengers, S2 - strategy of operation by a train of single buses with a capacity of 10 passengers each.

It can be seen (Fig 20) that the use of modular fleet provides an opportunity to reduce the costs of transportation organization by 72% [34, p. 398].

Similar conclusions on the assessment of the efficiency of using modular passenger vehicles in the works [35, 23] show the following its main advantages:

1. Increasing the speed of passenger transportation.
2. Reducing the cost of transportation.
3. Reducing the utilization of roads.
4. Reducing the negative impact on the environment.

In [36], the capabilities of modular passenger vehicles in providing regularity are shown. The authors consider three strategies to ensure regularity when a route vehicle is late from the schedule:

1. Lack of control. The route vehicle continues on the route without taking any action to restore the schedule.
2. Skipping stops. Some stops are skipped in order to "catch up" with the traffic schedule. In this case, passengers who wanted to get off at the skipped stops are forced to get off at the next stop where the stop will be made. Passengers at the skipped stops at this strategy incur additional time costs waiting for the arrival of the next route vehicle.
3. Module separation. The front module skips the stop, catching up with the schedule backlog. The rear module stops at all the stopping points. Passengers who need to disembark at skipped stops while the route vehicle is in motion are moved to the modules that will not skip stops.

The modeling results showed the following values of the estimated parameters for the above three strategies, respectively:

- Average passenger waiting time for MTS arrival, min: 7.3; 3.7; 2.2;
- Average time spent in the MTS, min: 23.9; 20.9; 20.2;
- Average duration of the whole trip, min: 39.3; 31; 24.9.

The paper [37] considers the technology of ambulance work when organizing such work with modular medical vehicles. The variant of two types of such vehicles is considered - life support vehicle and medical transport vehicle, which are realized in the form of modules that can be attached to each other and move the victim between these modules during the movement. The scheme of organization of mobile medical assistance is proposed, in which the life support vehicle is sent to the scene of an accident, there the patient is assisted and transportation to the transfer point begins. At this point, the life support vehicle is connected to a medical transport vehicle. The medical transport vehicle then transfers the patient, disconnects from the life support vehicle and continues transportation to the hospital for the hospital reception tasks. The life support vehicle then proceeds to the next incident scene. Performance simulations for Sioux Falls (South Dakota, USA) conditions showed the effectiveness of the proposed modular system by reducing the response time to emergency calls, decreasing the time to transport patients to the hospital and improving the overall performance of the ambulance system.

In [38], the problem of ensuring uniform intervals between route vehicles is considered. To solve this problem, the authors propose a strategy that combines separating or holding buses to adjust the intervals. Bus splitting means that when a bus is running late and the interval to the bus ahead becomes too large, it splits into two modular units that move along the route independently of each other. The first modular unit skips the stop where the bus was supposed to stop, and the second modular unit stops at that stop to pick up passengers. The first modular unit then stops at the next stop, where it waits for the second modular unit so that they can combine back into one bus. Bus retention means that when a bus arrives at a stop earlier than required, it is delayed at the stop to shorten the interval to the route vehicle ahead. These two techniques are combined into a new strategy that adjusts intervals that are shorter or longer than required. The authors conducted macroeconomic modeling on a bus route in Hangzhou, China, and compared their integrated strategy with other strategies. The results showed that the proposed strategy outperforms other strategies in reducing average trip cost and its variation, limiting bus congestion costs to less than 10% at realistic levels of system utilization.

In [39], it is noted that individual on-demand buses are a rapidly developing demand-responsive public transportation mode that can offer flexible non-disruptive and door-to-door travel options for passengers with the same time and space requirements. One significant advantage of on-demand buses over traditional fixed-route systems is that passengers can pre-book services through online platforms. This advance information (i.e., reserved requests including boarding and disembarkation points, and preferred time windows for these operations) allows optimizing passenger transport operations and reducing the cost of operation. At the same time, the main problem of this mode of passenger transportation is to satisfy the requests submitted in real time during the trip, while ensuring a high quality of service for both passengers already in the process of transportation and those who have just submitted such requests. This paper considers two different forecasting scenarios: scenario 1 (optimistic) and scenario 2 (pessimistic). The optimistic scenario assumes a high forecasting capability when sufficient resources and data are available to create sophisticated and high-quality forecasting models. For this scenario, a mixed integer programming model is developed using a spatio-temporal network to jointly determine module routing and scheduling, passenger assignment to modules, and module formation. The pessimistic operation involves limited forecast accuracy when simplicity is prioritized, forecast cost is relatively low, and advance passenger requests are highly irregular. A two-stage optimization procedure is applied to solve this problem. In the first stage, a deterministic model is used to generate conservative plans based on uncertain forecasts, including module movements and passenger assignments, with a minimum penalty for unserved passengers. In the second stage, control strategies are used to adjust plans, including re-routing, disconnecting (joining) modules, and reassigning passengers, to fulfill actual requests received during operation. Simulation of the operation of the proposed strategies using Beijing as an example showed the possibility of reducing transportation costs by up to 21%.

In [40], a novel flexible bus dispatching system is proposed in which a fleet of fully auto-coordinated modular buses, along with conventional buses, serve passenger demand. The authors developed an optimization model used to determine the optimal composition of modular buses and the optimal service frequency with which buses (both conventional and modular) should be dispatched on each bus line. Congestion dynamics and complex interactions between transportation modes at the network level are explicitly taken into account based on a recently proposed three-dimensional macroscopic fundamental diagram (3D-MFD). The three-dimensional macroscopic fundamental diagram (3D-MFD) is a concept that is used to model and analyze transportation systems by considering the complex interactions between different modes of transportation and passenger flows. It allows considering the dynamics of vehicle and passenger movements in three dimensions: Space, time and flow density. In the context of this paper, 3D-MFD is applied to optimize bus dispatch frequency and optimal utilization of bus modules in a flexible dispatching system.

The considered transportation network is based on the city of Zurich, Switzerland, and consists of five bus lines with different lane allocations. The simulations were conducted under three scenarios of MTS and passenger car traffic intensities - low (L), medium (M) and high (H) (Fig 21). For each scenario, the proportion of modular buses pm ϵ {0; 0.1; 0.2; 0.3; 0.4; 0.5;1} is also varied. The total number of conventional buses at pm = 0 is Fr = 50 units. Their capacity is 120 pax. When pm ϵ { 0.1; 0.2; 0.3; 0.4; 0.5; 1} Fr = 50 - (1 - pm). The capacity of the modules is 20 pax. The maximum number of modules that can be combined into a single bus is 6.

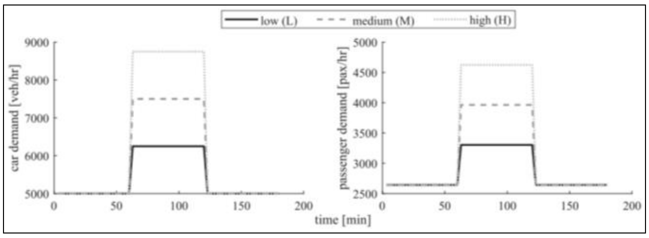


**Fig 21:** Modeling parameters: (a) automobile demand profile; and (b) public transport passenger demand profile [40, p. 50]

The operating cost per unit of time for conventional buses (πr) - representing the value associated with the cost of operating conventional buses, including drivers, maintenance, energy consumption, administrative costs and other operating costs, is 260 Swiss francs per hour. The operating cost per unit of time for one unit (πm) is CHF 30 per hour. These amounts are equivalent to 234 and 27 Euros / hour respectively.

Taking into account these initial data, the optimization of module assignment on the considered route network was carried out by the sequential quadratic programming algorithm with the number of starting points equal to 50. The results are presented in the form of diagrams of the total cost of public transport system operation (Fig 22), passenger delays (Fig 23), and the cost of operator services (Fig 24).

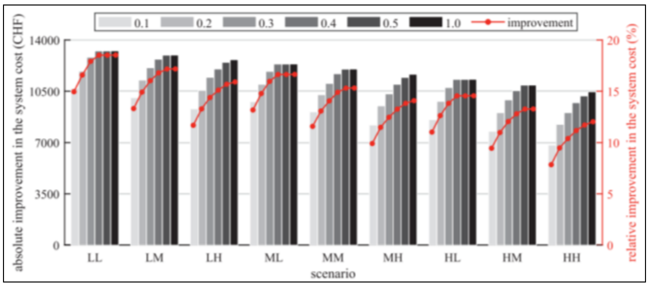


**Fig 22:** Comparison of total system cost improvement for different penetration levels of modular units [40, p. 51]

Traffic scenarios are represented as an XY plane, where X denotes the level of demand for cars and Y denotes the level of demand for public transportation: Low (L), medium (M), or high (H) (Fig 22). For example, LM denotes a scenario with low level of car demand and medium level of public transportation demand. As can be seen, the proposed system significantly outperforms the base case using only conventional buses, especially in scenarios with low car and public transportation demand. The potential improvement can be as high as 19% depending on the level of demand for automobiles and passenger transportation, as well as the penetration rate of modular buses. When the level of demand (particularly for car transportation) increases, the improvements become smaller but still significant. There are two reasons for this. First, when bus and car demand is low, the system dispatches a group of several combined (or even separate) modular units, thereby increasing vehicle capacity utilization and reducing operating costs. Second, due to the smaller number of units contained in a modular bus, the system has more units available, allowing more modular buses to be dispatched and reducing passenger waiting times. On the other hand, it has minimal impact on automobile traffic in case of low car demand due to less interaction between modes. Meanwhile, sending more modular buses when car demand is higher does not necessarily improve the system performance as the impact on automobile traffic may be significant, leading to a decrease in overall system performance. The situation is similar for the other variables studied (Fig 23, Fig 24).

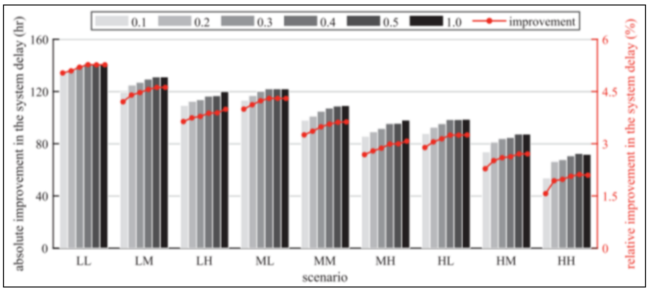


**Fig 23:** Comparison of system delay improvement for different penetration levels of modular units [40, p. 53]

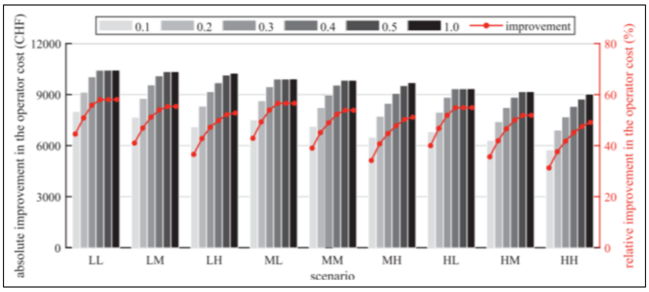


**Fig 24:** Comparison of carrier cost improvement for different penetration levels of modular units [40, p. 53]

It should also be noted that even with a small share of modular passenger vehicles, there is a significant effect on all of the above criteria. Further increase in the share of modular buses can improve the values of these criteria, but by a small amount. And in some cases, increasing the share of modular buses has no effect, as can be seen, for example, scenarios LL, LM, ML, MM, HL, HM (Fig 22), LL, LM, ML, HL, HM, HH (Fig 23), LL, LM, ML, MM, HL, HM (Fig 23).

Summarizing a brief analysis of scientific publications in the field of modular passenger vehicles, it should be noted that they are promising in terms of reducing the costs of passenger transport operation, as well as improving the quality of services provided to passengers. a number of their main drawbacks can be identified:

1. Putting such proposals into practice implies the creation of a fundamentally new passenger transport system in cities, where there may be no regular routes, no permanent timetable, and the passenger may have to change the module in motion. This will all require fundamental changes in transport legislation as well as human behavior.
2. The modular passenger vehicles under consideration should have modern digital devices that provide connection (disconnection), including in motion, of individual modules, as well as the ability to combine space within modules moving in the same train. Obviously, the cost of such devices will be high, especially for countries that will have to export them. And combined with the relatively low cost of fuel, drivers' wages and passenger-hours, the implementation of such transportation systems may not be economically feasible.
3. The given examples of calculations are based either on abstract initial data or on a part of routes of any city. I.e. there is no holistic methodology for managing the fleet of modular passenger vehicles, taking into account the redistribution of modules by routes, trips, restrictions on the drivers' work and rest regime, the capacity of final stopping points and other restrictions encountered in the practical activities of carriers.
4. Demand fluctuations depending on weather and calendar factors are not taken into account [41].

## 3. FCRPT in the Republic of Belarus

Much work on justification of a new system of passenger urban transport of flexible capacity has been done in the Republic of Belarus [42, 43, 44, 45, 46, 47, 47, 48, 49, 50, 51, 52, 53, 53, 54, 55, 56, 57, 58, 59]. The type of transportation proposed in these works is a system in which information processes (information collection, information processing, decision making) are performed continuously and form the basis of the information transportation system. The single vehicle of the system is an autonomous electric car called an infobus (Fig 25), which moves along a separate railroad track.

**Fig 25:** Infobus [45]

The infobuses are assembled in cassettes consisting of a varying number of units. The connection is virtual, as in road trains. The minimum safe distance between the infobuses in a cassette is ensured by electronics. For more efficient organization of this transport system, a passenger entering a stop passes through a terminal where he pays for the fare and indicates the destination stop. When a sufficient number of requests are accumulated, infobuses go to the route and perform transportation between the stops of the route in accordance with the received requests.

To reduce interference from other vehicles, it is proposed to allocate special lanes, as it is done for public transport such as buses or trolleybuses, and to cross roads at different levels.

The system proposed by the authors is a well-founded theoretical model of a new type of passenger transport, which will reduce the carrier's costs for passenger delivery by adjusting the capacity of used passenger vehicles to the actual transport demand. In addition, it is supposed to improve the quality of services provided to passengers by reducing the number of stops passed by the infobus on the route.

At the same time, the analysis of such a system shows the presence of a number of issues and shortcomings, some of which can be attributed to the above described modular passenger vehicles:

1. How to take into account the possibility of boarding passengers not in their infobus?
2. It is indicated that the cost of 1 km of metro is about 50 million dollars. At the same time, it is not clear how much the infrastructure for the proposed mode of transportation will cost (terminals at bus stops [48], infobuses, hardware and software, multi-level paths through the intersection [49], information boards at each bus stop [49], monorail, etc.).
3. Giving traffic priority to infobuses [44] will reduce the capacity of the UDS for other vehicles.
4. A passenger specifies a destination station by passing a terminal at a stop, and waits until the correspondence matrix is formed. And if it will be formed for a very long time (condition 1 in [49] is not fulfilled)?
5. How does a passenger find out which of the infobuses approaching the stop he should board, since there will be no fixed routes according to the author's opinion? Through a cell phone? And if there is no cell phone or the battery is dead?
6. The passenger must know all the stops well to know which one to get off at, otherwise he will not be able to indicate his destination at the terminal.
7. The authors used in their calculations the engine efficiency of 25% [46], while it is actually about 50%.
8. The authors suggest different infobus capacity from 6 to 70 passengers and there is no justification for the specific capacity.
9. The presence of an intruder who has parked his car on the infobus path or a driver who has made a forced stop jeopardizes the functioning of the whole system.
10. It is not clear how to set the values of k (the proportionality factor by which the preference (ratio) between ATP losses and passengers is established) and T (patient waiting time) given in [55].
11. A driver who needs to leave for a trip boards the first bus in the queue, which will be the head of the caravan [56, p. 132]. This does not motivate the driver to take care of the bus they drive, which may cause frequent breakdowns.
12. In [52, page 3] it is stated that urban automatic transportation can provide almost zero waiting time and non-stop travel from the point of departure to the point of destination, which based on the described technology of its operation is not possible. So, the passenger needs to specify the necessary information on the terminal of the stopping point, which is accumulated up to a certain moment, only then the cassette of infobuses leaves for the first stopping point and until it reaches the stopping point where the request is submitted, some time will pass and it is not a fact that this waiting time will be less than the waiting time of the passenger arriving at the stopping point in the existing system of transportation organization taking into account the constant schedule. Non-stop travel is also difficult to achieve. For example, if the capacity of the infobus is 30 passengers and for its occupancy it is necessary that between each pair of departure and destination points 30 passengers traveled, which corresponds to the volume of transportation on the route per trip equal to 30*N, where N is the number of pairs of departure and destination points. Then, on a route of 10 stopping points, the set of pairs N will look as follows {1-2; 1-3; 1-4;....;1-10; 2-3; 2-4; 2-5;....;2-10;... 9-10}. In general, the number of such pairs is N*(N-1)/2, which is 45 pairs for a route of 10 stops. If 30 passengers are transported between each pair of stops, the total volume of transportation on the route should be 45*30 = 1350 passengers per trip. The practice of passenger flow survey [60, 61, 62, 63] shows that in more than 80% of cases up to 100 passengers are transported per trip (Fig 26) and shows a low probability of transportation process organization without intermediate stops.

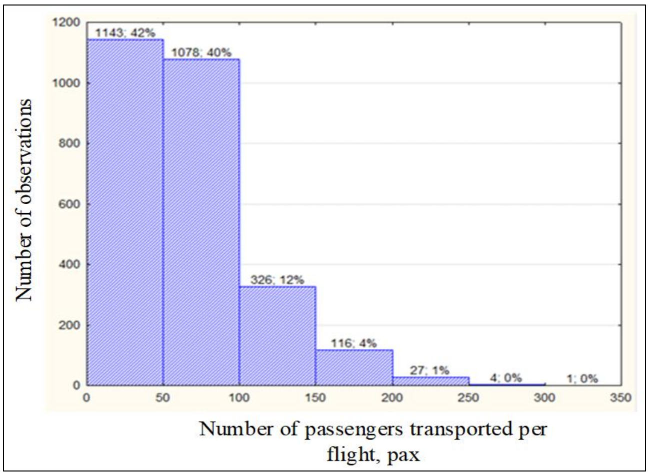


**Fig 26:** Histogram of distribution of the number of passengers transported per flight

13. The results presented in [64] show that passengers, including those who use private cars, believe that on-demand public transportation is appropriate in cases of low passenger traffic. In cases of stable and high passenger traffic, passenger transportation should run on a schedule, so that its users can plan their time based on this schedule.

The works [65, 66, 41] also proposed a new system of modular passenger transport, which in contrast to [42, 43, 44, 45, 46, 47, 47, 48, 49, 50, 51, 52, 52, 53, 53, 54, 55, 55, 56, 57, 58, 59] does not require significant investments in infrastructure and changes in transport behavior.

In order to avoid the problems described above, [65] proposed the use of modular TCP trains, which allow to reduce or increase passenger capacity depending on the passenger load for each flight (Fig 27). During the period of passenger traffic decline, passenger load is reduced and the flight is performed by a modular TCP train consisting of one module (Fig 27, a). In case of passenger traffic growth the passenger load increases and at the final stops the necessary number of modules is added to the modular TCP train, providing the required total capacity of the modular TCP train (Fig 27, b). In this case, the technology of organizing the work of such modules provides for minimizing the difference between the capacity of the modular TCP train and passenger load.

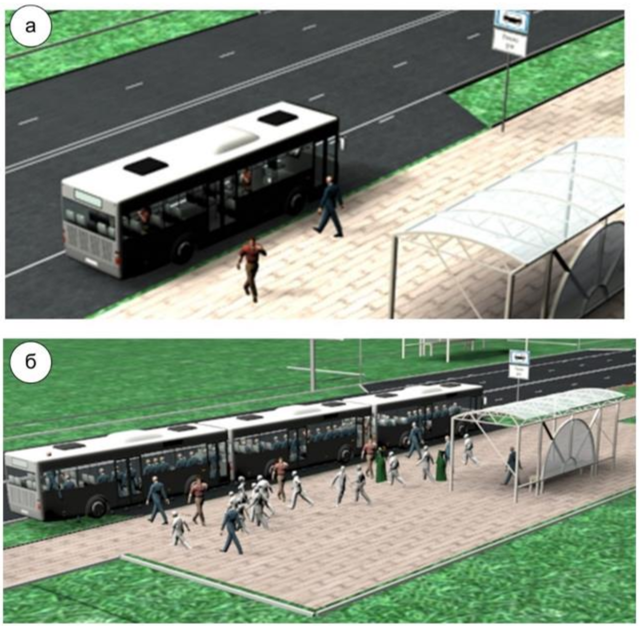


**Fig 27:** Use of modular vehicles: a - one module during periods of passenger traffic decline; b - three modules during periods of passenger traffic growth

Modeling of work on such technology on 16 bus routes of Gomel showed that at the value of the capacity utilization factor of 0.55 self-sufficiency of passenger transport operation is observed [65]. Modeling of application of such technology of passenger transportation organization on 1747 trips made on 81 city routes of Gomel and Mogilev showed an increase in the payback of passenger transport operation from 69.7% to 81% [66]. Modeling of the application of such a system, taking into account the dependence of passenger flows on calendar and weather factors, has shown an increase in the payback of work on the studied turnaround route by 39% (from 79.8% to 110.6%), a decrease in the cost of its performance by 41% (from 7.74 to 4.59 USD), annual savings of about 2.38 million USD per year for the entire city of Gomel. The approximate payback period does not exceed two years [41]. To ensure the "adjustment" of the capacity of modular passenger vehicles (see Fig 27) to the actual passenger flow on each flight of each route, an intelligent control system for regular passenger transportation is proposed (Fig 28).

As can be seen (Fig 28), the daily information from the passenger counting sensors goes to the server, from where the information about passenger load on each flight of each route is extracted. Here, the operator also enters daily calendar information (day of the week, its type, month, etc.) as well as information about the weather forecast for the next day. Based on the array of such entered information, a daily forecast of passenger load values on each flight of each route for the next day is built. On the basis of such forecast values, as well as taking into account the available fleet of TCPs, including modular ones, and the structure of the route transportation network, multiroute distribution of TCPs for operation on each flight of each route is made.

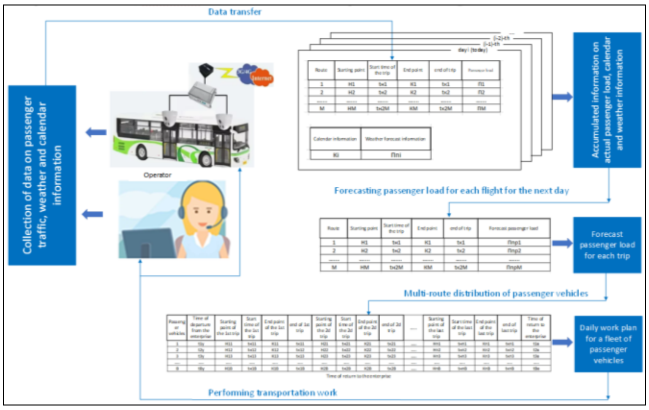


**Fig 28:** Scheme of operation of the proposed intelligent control system of FCRPT]

Thus, the approach given in [65, 66, 41] to the organization of work of a regular passenger vehicle implies the presence of a passenger counting sensor in each module. Of course, this is an additional capital investment, but its value at the moment is quite acceptable and such investments are paid off in 2 years [41]. Also, the implementation of this approach does not require a serious revision of transport legislation and passenger behavior, which is an additional aspect in favor of its implementation. The main problems remain:

1. Lack of production of modular passenger vehicles on the territory of the Republic of Belarus. This is primarily due to the legislative ban on the participation of passenger vehicles in road traffic. As the above analysis of publications shows, the existence of such bans is an unreasonable measure that should be reconsidered.
2. There is no substantiated technology of module distribution on route flights taking into account objectively existing passenger loads, restrictions on drivers' labor and rest regime, capacity of final stopping points, etc.

A summary table of the results of the analysis of scientific literature in the field of FCRPT is given in Table 1.

**Table 1:** Summarisation of scientific sources on the application of FCRPT

| Publication | Target function | The values obtained | Attaching (disconnecting a module) | Passing of stopovers | Routes | Description of source data | The best effect obtained |
|---|---|---|---|---|---|---|---|
| [27] | (transfers in traffic + total number of modular bus movements)→min | Plans for making transfers, couplings and uncouplings, as well as their locations | At all stops. | Allowed | Non-permanent | abstract road network of four intersections | 15% reduction in the number of transfers, 14% reduction in average journey time |
| [28] | $(P_c + C_o) \rightarrow min$ | Plans for the execution of transfers, couplings and uncouplings, as well as their locations | At all stops. | Allowed | Fixed | 10 lines of the Barcelona route network: 5 with the highest demand and 5 with the lowest demand. Operating period - 24 hours | 17, 4 % reduction in the value of the target function for route D40 when applying strategy S3 compared to conventional bus services |
| [32] | $S_{mav} \rightarrow min$ | Coupling and uncoupling execution | At the initial stops. | Not allowed | Fixed | Northeast sector of Singapore | A 44% reduction in the value of the target function on trunk |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | plans | | | | | routes and a 37% reduction for feeder routes |
| [33, 35] | $(C_{pw} + C_f) \rightarrow min$ | Number of MAVs and route for each departure | At the initial stops. | Not allowed | Fixed | abstract route in one of the districts of Tampa (Florida, USA) with abstract values of passenger traffic for 2040, equal traffic intervals. | More than twofold reduction of fuel (energy) consumption costs with the use of modules compared to conventional buses |
| [34] | $(C_o + C_{pw} + P_c + C_s) \rightarrow min$ | Coupling and uncoupling schedules, when to work on flexible routes and when to work on fixed routes | At the initial stops. | Not allowed | Non-permanent or fixed depending on demand | abstract route, within an hour | Savings of $3.89/hour per route |
| [36] | $(C_{pw} + P_c + C_s) \rightarrow min$ | Execution plans for module couplings and uncouplings | At all stops. | Allowed | Fixed | abstract route with 20 stops | Reduction in average journey time from 39.3 min to 29.4 min (25.2 %) when implementing the strategy of module separation on the move, compared to no such separation |
| [38] | $(C_{pw} + P_c + C_s) \rightarrow min$ | Execution plans for module couplings and uncouplings | At all stops. | Allowed | Fixed | Bus route number 3 in Hangzhou, China | Reduction in average journey time from 29.7 min to 25.2 min (15%) with a strategy that combines bus segregation and bus delay, compared to a strategy with bus delay alone. |
| [39] | $C_o \rightarrow min$ | Routes, schedules, module coupling and uncoupling plans | At the initial stops. | Not allowed | Non-permanent | Suburban route network of Beijin, China. Beijin, China. from 3 December 2018 to 18 January 2019 for training and days from 21 to 25 January 2019 for testing. Trip data are taken from smart card data | Compared to the real-time approach, the proposed system reduces operating costs by 21% when applying an optimistic passenger forecasting scenario. |
| [40] | $(C_o + P_c) \rightarrow min$ | Number and frequency of MAVs used | At the initial stops. | Not allowed | Fixed | 5 Zurich routes with shared and dedicated lanes. 1 hour each during periods of high, medium and low traffic demand. | almost 60 per cent reduction in operating costs (during periods of low traffic demand) compared to the modular bus option |
| [41] | $(C–P) \rightarrow min$ | Планы выполнения сцепок и отцепок | At the initial stops. | Not allowed | Fixed | Annual data on passenger load on a turnaround trip of one bus route of Gomel city for a year. | Increase of payback of work on this turnaround flight by 39% (from 79.8% to 110.6%), reduction of its cost by 41% (from 7.74 u.u. to 4.59 u.u.), annual saving of about 2.38 million u.u. per year for the whole city of Gomel. The estimated payback period does not exceed two years |
| [42, 43, 44, 45, 46, 47, 48, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59] | - | Plans for the execution of transfers, couplings and uncouplings, as well as their locations | At all stops. | Allowed | Non-permanent | Abstract data | - |
| [65] | $(C–P) \rightarrow min$ | Coupling and uncoupling execution plans | At the initial stops. | Not allowed | Fixed | Part (16) of Gomel bus routes | At the value of the capacity utilisation factor of 0.55, self-sufficiency of passenger transport operation is observed |
| [66] | $(C–P) \rightarrow min$ | Coupling and uncoupling execution plans | At the initial stops. | Not allowed | Fixed | A part (1,747) of rides made on 81 urban routes of Gomel and Mogilev city | Increasing the payback rate of passenger transport operations from 69.7% to 81%. |
| [68] | $(S_{mav} + C_f + C_{pw} + P_c + P_s) \rightarrow min$ | Number of MAVs and route for each trip, MAV coupling and uncoupling scheme, MAV skip scheme | At all stops. | Allowed | Fixed | Bus route 110 in Dandong, China, 13 stops, 7.2 kilometres, 10:00 to 11:10. | 32 % reduction of the target function in the proposed scenario compared to the scenario of module movement without skipping stops |
| [69] | $(C_o + C_{pw} + P_s + P_c) \rightarrow min$ | Number of MAVs and route for each departure | At the initial stops. | Not allowed | Fixed | - | - |
| [70] | $(C_o + C_{pw}) \rightarrow min$ | Number of MAV flights and route for | At the start terminals and the | Not allowed | Fixed | - | - |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | each departure, number of MAV flights for branched routes | last stop of the overlapping segment | | | | |
| [71] | ($P_c$+ $P_s$ + $C_o$ + station relocation cost+ station construction cost) →min | Location and capacity of the constructed station, MAVs coupling and uncoupling scheme MAVs coupling and uncoupling scheme at the constructed station | At the stations that have been built | Not allowed | Fixed | - | - |
| [72] | ($C_o$ + $C_{pw}$) →min | Route, connection and disconnection scheme of MAVs | At all stops. | Not allowed | Fixed | A group of cities in Switzerland consisting of 15 nodes and 21 bidirectional links, peak hour transport demand matrix | 100 per cent reduction in operating costs with the proposed system compared to the current system |
| [73] | ($C_{pw}$ + $S_{mav}$) →min | MAV coupling and uncoupling diagram, timetable | At all stops. | Not allowed | Fixed | Nantong (China), from 5:00 to 21:00. A round trip on a route with 10 stops on each trip. | reduction of the target function by 50 % in the periods of lowest intensity regardless of the applied timetable category |
| [74] | ($C_{pw}$ + $C_o$ + затрат на восстановление баланса) →min | Путь следования, количество MAV на остановках | At all stops. | Not allowed | Fixed | - | - |

$S_{mav}$ – MAV cost of ownership;
$C_f$ – fuel (energy) consumption costs;
$C_{pw}$ – costs for passengers waiting for the arrival of a passenger transport vehicle;
$C_o$ – operating costs
$C_s$ – the cost of getting to and from the stop
$P_s$ – penalties for passengers skipping the MAV due to its overcrowding
$P_c$ – passenger travel costs
C – passenger vehicle capacity
P – passenger load.

## 4. Conclusion

This article considers the actual task of applying FCRPT in the practical work of regular urban passenger transport. It is noted that in the countries of the former USSR this method of improving the efficiency and quality of services provided to passengers is practically not considered. This is due to the existing stereotypes of the negative impact of trailed passenger vehicles on road safety. At the same time, it is shown that the practice of using trailed passenger vehicles has a century-long history, including in the former USSR, and high popularity in developed countries at present. The main scientific publications on this subject available in the public domain have been analysed (Table 1). The main problems of realisation of technologies of FCRPT work proposed in such publications are shown. It is proposed to implement an intelligent system of regular passenger transport management in the Republic of Belarus (Fig 28), which implies the use of modular passenger vehicles (Fig 27) and daily forecasting of passenger load for each trip of each route with the subsequent assignment of a train with a capacity corresponding to such passenger load. Tentative calculations show that the implementation of such an intelligent control system will make urban passenger transport break-even, and the payback period of such a project for the conditions of Gomel does not exceed two years [41].

The main problems hindering the use of FCRPT in the territory of the Republic of Belarus are highlighted:

1. Lack of production of modular passenger vehicles on the territory of the Republic of Belarus. This is primarily due to the legislative ban on the participation of passenger vehicles in road traffic. As the above analysis of publications shows, the existence of such bans is an unreasonable measure that should be reconsidered.
2. There is no substantiated technology of module distribution on route flights taking into account objectively existing passenger loads, restrictions on drivers' labour and rest regime, capacity of final stopping points, etc.

The mentioned problems are the main directions of scientific works in this sphere.

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