Modeling the Influence of Fixed-route Network Operational System on the Area Service Quality

Piotr Czaja
International University of Logistics and Transport In Wroclaw, Poland

Fixed-route networks constitute a category of transport infrastructure systems. As a fixed-route transport system subgroup they present a combination of transport solutions related in terms of operating properties. Owing to property criteria systematization, an analysis of the fixed-route system regarded as a part of a fixed-route network category is of higher cognitive value than a separate, fragmentary examination of its particular representatives.

1. FIXED-ROUTE NETWORKS

Fixed-route infrastructure denotes most often roads, transport points (stops, stations etc.), as well as auxiliary devices used directly to service the rail-based transport roads and ports. In general, fixed-route transport means that vehicles can run only along a track typical of a particular technology. Fixed-route networks have a broader meaning [4]. A vehicle is assumed to be guided by the infrastructure in these networks. It cannot pass a vehicle running in front of it on the same track without changing the track (it should make a detour). It cannot leave spontaneously the previously chosen track, with the exception of detours, without using auxiliary technical means which don't support its scheduled drive (cranes, temporary crossovers provided in order to enable a detour). The track change (exit from the planned line) is always enforced. The exit from the planned line may be caused by organizational or technical network segment blockage (changes in road traffic organization, a vehicle breakdown, an accident), infrastructure segment breakdown (sudden damage) or a planned shutdown when infrastructure elements are being conserved or repaired (for example, planned infrastructure elements replacement). The vehicle is also assumed to run according a prescribed route and to have an independent drive enabling it to move. A great number of transport systems define the fixed-route network concept that way. As a system category, it combines transport solutions with common operating properties.

As the category is very numerous and its representatives have significant differences, it itself is subject to division because of the kind of its components and network nodes. Fixed-route networks are divided into four basic groups [4]:

- 0r networks,
- 1r networks,
- 2r networks,
- kr networks (where $k \geq 3$),

with different apply and network topology properties of their representatives.

0r networks consist exclusively from straight segments. Stacker cranes moving in parallel aisles that are not connected with each other are an example of systems belonging to that group.

Track layouts belonging to that group are grade-separated provided that not more than one vehicle is driven on one track. Collision situations should be allowed for in the case of a few vehicles because of the necessity to move along the same track in two directions. Crossroads are allowed in more complicated layouts. These networks are rarely used because of the low flexibility of their network topology.

1r networks consist from straight segments and curves. Devices carried along the inductive path or vehicles driven on rails in track layouts having no junctions are an example of systems belonging to that group.

As the track cannot be changed, these networks are often grade-separated (as long as more vehicles running on one track, or crossroads, are not introduced, as it was in the first case). The possibility to move in a closed cycle (in a loop) on a one-way track increases the network efficiency by adding further vehicles.

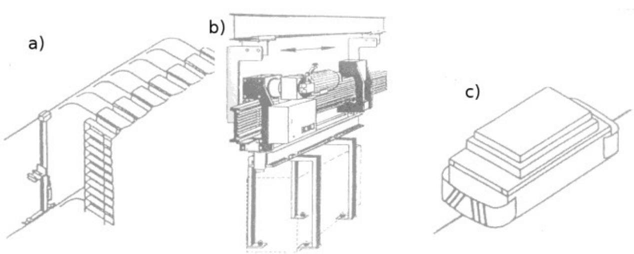

Fig. 1 Examples of fixed-route systems in the internal transport: a) stacker crane, b) transmotor, c) mobile robot of the second generation guided with the help of the inductive path.

2r networks are systems comprising straight segments, curves and crossovers owing to which the choice between two alternative roads behind the network node is possible. Tram networks in most their implementations are an an example of systems of that kind (the use of more complicated crossovers is technically possible but in practice they are not used in Poland).

A strong probability that collision situations will occur should be taken into consideration in networks of that kind, which influences significantly the network traffic organization. As a kind of topology, these track layouts are very flexible, they freely build up the network density regulating the network subarea level of service.

Kr networks (where $k \geq 3$) are the networks in which straight segments, curves and crossovers of any kind are used. They are very rarely used in practice.

Fixed-route networks are also divided according to secondary criteria that are applied to the mentioned above transport system groups. The criteria are the following: area service evenness (homogeneous and heterogeneous networks), network structure homogeneity (regular, irregular), movement direction dominance (directed, undirected), space limitation (limited, unlimited).

2. FIXED-ROUTE NETWORK PROPERTIES

Secondary criteria diversifying main groups into which the fixed-route network category is divided single out specific properties of particular transport systems.

Area service evenness is possible in each kind of network in the fixed-route network category and it helps to reach the same level of service of the whole area that is served. Both the evenness of the whole network and that of its definite parts, in which exactly that property is required, is allowed.

Structure homogeneity is a network property resulting from the fact that its topology is the result of a repeated basic module. The module itself is most often a simple track layout with a constant number of entrances and exits, as well as their regular arrangement which enables a free module combination.

If a particular network contributes to the appearance of transport lines with the same direction of route, then it reveals the movement direction dominance and the network itself is considered directed. This property is the most intensive in regular 2r networks, as their construction makes one take into account the movement direction dominance while designing transport systems.

Design with the smallest possible surface available for a transport system is due to following the prescribed and fixed track. For fixed-route networks help to keep the minimal differences between the vehicle and infrastructure extremes.

Sensitiveness to network link shutdown is the main operating property common to all the fixed-route network systems. The disruptions that then occur are propagated in the network very quickly and in an unpredictable way. It's also difficult to lay down the measurement parameters of quantities that would specify the consequences awaiting a network operator in a way adequate to the actual state and to diverse subjects involved in transport processes.

Link shutdowns occur in each operative fixed-route network. They are caused by the necessity to keep the infrastructure in a proper state while the strategy of their implementation and their effects are mainly dependent on the applied transport technology and network topology.

When the network link shutdown on the planned route is inevitable, it's possible to restore the line continuity between its final points by using a detour.

A detour is assumed to be a set of organizational and technical activities aimed at restoring the line continuity lost because of a particular route segment shutdown, without the necessity to change the means of transport and transport technology.

In some circumstances the line continuity restoration is impossible. The decision on the line disconnection may be made in that case.

The line disconnection denotes its continuity break-off accompanied by the lack of justification (or technical unfeasibility) for making a detour of a segment where the passability was lost.

In a special case when the passability is lost not far from the line end, the decision to cut off the line may be made.

The line cut-off denotes its disconnection which means that the line segment comprising its shipping /receiving terminal is no longer operated.

If several lines are cut at the same place then the decision to connect the line may be made.

Two independent lines being joined into one (one transferring into the other) because of their previous cut-offs are considered the line connection.

Suspended and substitute routes constitute another particular property of some fixed-route systems, which refers to network link shutdown.

Traffic disturbances on a line can lead to a situation when the transportation on this particular route is impossible and possible traffic guidance scenarios available in the system lose the initial route goal (the routes are too different in their course from the initial route). In this case the line traffic suspension as well as transferring, if possible, transportation tasks on other means of transport with a different transport technology (for example, trams may require substitute bus lines), is the only solution.

Disturbances on a line, in a degree that makes a given line lose its identity due to alternative transportation means, can lead to one or more substitute lines designation. These lines are new network routes which partially make up for the initial line transportation tasks suspension.

Transferring transportation tasks on other network lines is an exceptional situation. Such a scenario is exceptional because under normal circumstances the other lines are to reach other goals set when designing the network. Nevertheless, if a line course is changed (for example, because of a detour) then it's possible that its new route can be considered substitute in relation to another independent line which is currently suspended.

All the presented above fixed-route network properties and their accompanying consequences influence the transport processes quality while defining the operating conditions.

3. OPERATIONAL EFFICIENCY ASSESSMENT

Efficiency was chosen as a superior assessment criterion of fixed-route network operation influence on the area service level. Efficiency assessment is most commonly used as a superior system assessment criterion and as a multi-discipline issue, it represents various approaches.

There are major differences in its interpretation with regards to transport systems [1]. A. Brandowski's definition is esteemed to be the most relevant in description of fixed-route network usage [2]:

Def. 1. Technical system efficiency in a descriptive sense constitutes a joint system and its operation process property which assesses the system use consequences.

Def. 2. Technical system efficiency in a normative sense constitutes a degree of system tasks realization possible under definite conditions at a particular time interval.

If the first efficiency definition is accepted then a synthetic index of transport system assessment can be specified, which assesses the system as a whole in relation to issues on its usage. This definition focuses on the quality efficiency dimension covering an overall system assessment and system activity consequences for the environment. It's a global approach in a fixed-route system assessment.

The above mentioned incidents connected with network links shutdown reduce its efficiency. Being undesired yet unavoidable, they must be limited. That's why their partial assessment is presented in terms of a penalty.

A system can be assessed at the final stage of its design at the earliest. The system that is assessed is assumed to be properly constructed and all its parameters are considered to be based on the grounded design decisions. That's why the ensuing system is assumed to be efficient on condition that all the lines act in a planned way prescribed by the design and that there are no network work disturbances caused by the system infrastructure.

Taking into account the global character of the operational efficiency defined in accordance with the first definition we can consider the level of acceptance for network traffic quality reduction and the network efficiency to be the criteria for measuring this efficiency.

On the railway, for example in Tokyo, networks are already being assessed by determining the tolerance degree for traffic quality reduction when making decisions about traffic organization and operation strategy aimed at maintaining the infrastructure technical efficiency.

The efficiency measure for the acceptance criterion is derived from the acceptance function described, among other, in [3].

Efficiency, as a factor in fixed-route network assessment, refers to the degree of goal realization and network potential use. The goal realization degree considers the system's effect on the surroundings. The fact that networks can be partially, locally effective (for example: a network being effective on a number of lines while the remaining network area is subject to conditions that prevent vehicles from moving) means that efficiency seen from that perspective may be determined in a multi-degree way measuring the degree of network potential use indirectly. The measure of efficiency is determined by the goal realization degree.

In the case of fixed-route networks with their function of transferring load and people, the level of passengers' discontent, traveling quality and load transfer quality is dependent on the distance or time difference in comparison with the planned value. Distance or transportation time change regarding the scheduled timetable will thus be a reference value for the measure of penalty when assessing the level of acceptance for traffic quality loss.

Fixed-route network's goal is to service designated shipping and receiving terminals, as well as to transport passengers and load between those terminals. The measure of efficiency should determine the terminal level of service and the amount of penalty depends on the number of omitted terminals that are served in the network. In the case of fixed lines it also reflects the necessity to keep the normal (planned) route.

A penalty ascribed to fixed-route network irregularities is thus caused both by the line routes change and by the fact that the designated terminals were not served. That's why it can be represented as a function of many variables: a time and/or route difference and omitted line stops. These variables result from separate, previously established assessment criteria and as making conclusions on their positive correlation is ungrounded, they may be considered separately, as the final index components.

The route and the time during which it is covered are being determined while considering a vehicle movement in a fixed-route networks. In real systems the route is only slightly dependent on the time which is due to technical conditions and the influence of surroundings. Nothing more than a hypothesis can be formulated stating that a vehicle is likely to cover at least a definite distance. A connection between the route and the time is thus not defined deterministically and because of that the functional dependence is not precisely specified.

In a subject assessment, when a passenger or a load is regarded in a transportation process, the movement is connected with a choice of the means of transport and time reservation. The route covered while moving towards the target point (a subject perspective) is of minor importance. Most often the undertaken activity is assumed to be successful, and it's its quality that is subject to assessment. If it's uncertain whether the target will be reached then the time interval during which the subject remains in the transport system may be also considered uncertain. Such an approach is intuitive and commonly met in a transport process analysis.

When it's a transport infrastructure that is chosen as the assessment subject then the described value of the route and the time is changed. On the railway, where only one train at a time can stay on the station track or mainline track segment, the track reservation leads to its permanent unavailability which changes the network configuration for the other trains moving in the network at a certain point in time until the segment is vacated. A value defining the position and the covered route in relation to time increases. Nonetheless, the time remains a significant factor determining the network state. Considering the time as the penalty variable we introduce an aspect of dynamically changing network topology into the analysis, which has a negative impact on the result interpretation.

If line segments are not being reserved in a particular network, then from the whole network's perspective one can observe some indefiniteness of the means of transport's position in relation to time. Having only a network timetable at your disposal you can determine a vehicle position at a given point in time only with some precision. Even if the time is very short, the position indefiniteness is significant (provided that a vehicle isn't monitored externally, for example with the help of GPS) and position dependence from time is random for a great number of a certain route courses. The network potential use in relation to time is thus determined imprecisely, too.

The topology meaning in fixed-route networks taken into account, the difference between the route covered because of network disturbances regarding the fixed route is a prevailing value as a penalty variable connected with the traffic quality acceptance. This quantity refers not only to a particular vehicle movement but it includes its influence on the whole network as well. The longer a substitute route is, the less is the network potential needed to produce the same effect as in the case of the planned route.

Efficiency global assessment, expressing the fixed-route network efficiency in a descriptive sense, results thus from the function of penalty which decreases it. The penalty variables are the following: the difference in the length of the route caused by network work disruption and the number of unserved network points constituting the line shipping/receiving terminals.

A modified function arctg describes the shape of a curve describing a route change penalty resulting from a detour best of all [4]:

$$g(x) = arctg\left(\frac{a \cdot x^3}{L^b}\right) \cdot s$$

where: a,b – shape cofactors, x – a change in the length of the route, L – the length of the normal (planned) line, s – the g(x) function normalizing factor which corrects its maximum value making it equal 1.

A parameterized logistic function is used to describe the shape of a curve determining the penalty for unserved shipping/receiving terminals on the line route. [4]:

$$h(y) = \left(\frac{1}{1 + z \cdot e^{w \cdot \left(\frac{y}{P}\right)^c}} - f\right) \cdot u$$

where: y – the number of the omitted line shipping/receiving terminals, P – the number of the line shipping/receiving terminals that are being served, c,w,z – shape cofactors, f – a normalizing factor which corrects the saturation level of the logistic function increase up to value 0, u – a normalizing factor which corrects the function maximum value making it equal 1.

Fixed-route networks are sets of transport lines. These lines are defined by nodes and links covered during a vehicle movement. The network functional assessment is thus the assessment of particular lines which considers their meaning in the network. One of the assessment's objectives is to compare two different fixed-route networks of the same kind (but of a different size and topology). In order to get an aggregate result for separate lines so that one could compare different networks, it's necessary to accept one common minimum and maximum penalty value for the analyzed routes. Differences between the lines (length, traffic intensity, etc) determining their meaning in the network should be taken into account. Estimating the amount of money related to the loss incurred is the most commonly used form of penalty which doesn't meet these requirements. A non-dimensional indicator is the most appropriate unit determination form demonstrating the required properties.

The form of the second efficiency definition proposed by A. Brandowski is the basis for formulating a supplementary, local assessment. It is connected with the definite network topology assessment which influences the operating parameters of separate links. The latter transfer them onto individual lines and line layout. The local assessment has a parametrical indication character and the normative efficiency definition is expressed by it.

4. FIXED-ROUTE NETWORK OPERATIONAL SYSTEM AND AREA SERVICE QUALITY

Route changes caused by a network link shutdown due to planned repair and incidents are one of the most commonly used problems in the case of transport infrastructure usage. Each separate transport technology displays variable sensitiveness and consequences caused by the network link shutdown. The property consequences are measured with intensity which is dependent on the influence that can be exerted on vehicles' route change. They are especially discernible among technologies with a fixed movement route.

The category of fixed-route networks that was singled out constitutes a group of fixed-route transport systems with common operating properties. Those properties not only influence strategies undertaken to maintain the network efficiency, but also have a direct impact on the level of service of a particular area.

This influence can be expressed by a global assessment index of operational efficiency owing to which a particular area service quality can be cotrolled by:

- scheduling works connected with the network infrastructure maintenance,
- controlling the shutdown and detour arduousness,
- helping to make decisions about the network modernization legitimacy,
- selecting the best line detour while ensuring the accepted level of service of all the network shipping/receiving terminals,

The efficiency index enables the transport service quality control of a particular area at a particular time interval.

A particular fixed-route network track layout assessed from the perspective of the area service quality is determined by the following function variables: the length of the route's change caused by network link shutdown on its scheduled route and the number of omitted network terminals that are being served by these lines.

An analysis carried out in the case of Wrocław tram network showed that the part of a considerably broader assessment model of fixed-route network transport infrastructure presented in the article displays the network use properties adequately to real circumstances enabling the control of its basic parameters, including the service quality of the area where the network is located.

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