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SERVICE POLICY OPTIMIZATION FOR URBAN PUBLIC TRANSPORT NETWORKS: MOBILITY CONSTRAINTS DURING HEALTH EMERGENCY OF PANDEMIC CYCLES

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ABSTRACT: *This work presents an approach to model the behaviour of urban public transport networks for optimizing the service policy, which includes the effect of mobility constraints on health emergency for pandemic cycles. During health emergencies, local governments strongly use two regulatory policies for contain a disease spreading: (i) social distancing and (ii) restriction of social interaction; these regulatory policies thoroughly affect the urban mobility. We propose the optimization of a stochastic discrete-event model based on a passenger demand analysis by means: (i) a numeric model of a multimodal network considering interdependencies and asymmetries of passengers; (ii) an integration of the regulatory policies for health emergency; and (iii) a process for optimizing the passengers waiting time cost. This work is applied to an actual metropolitan transport network comprised of metro, tramway, and ropeway lines.*

KEYWORDS: *Optimization process, public transport network, system simulation, transportation system, urban system.*

1 INTRODUCTION

Health emergencies on pandemic cycles have massively affected the lives of people all over the world. Countries must take drastic measures to contain outbreaks (de Haas *et al.*, 2020) and they have put in place restrictive measures in order to confine the pandemia and contain the number of casualties. Among the restrictive measures, Urban Public Transport (UPT) constraints are certainly quite effective in reducing the mobility on the local scale in the short term but it also has high social impact on the long and short term (Iacus, 2020). The trend of UPT has been rising over the last decade at a pace that is faster than the population growth (Recchi *et al.*, 2019). Nevertheless, mobility flows have been shaped at regional scale by shocks due to operational and service policies (Gabrielli *et al.*, 2019). In addition, UPT has shown strong dependency on pandemia outbreaks in the past such as SARS in 2003, MERS in 2015 (IATA, 2020), and Covid-19 in 2020 (Bucsky, 2020), with effects that had repercussions at local and regional scale.

The circumstances result in situations in which people have had to change their daily life radically. People's activity patterns, the way they work and how they travel are three facets of daily life that have changed drastically. From both a research and social point of view, it is important to assess the mobility to these externally induced changes (de Haas *et al.*, 2020). Researches show that not only travel patterns, but also activity patterns are less stable during pandemic cycles (Hilgert *et al.*, 2018). Daily

travel behaviour particularly depends on habit and routine (Schönfelder and Axhausen, 2010). However, several studies have shown that there are certain events in people's life course that trigger change in travel behaviour (Müggenburg *et al.*, 2015; Schoenduwe *et al.*, 2015).

Social distancing measures (the social isolation and the passenger transport restriction) have important effects on the service transport, i.e., the Passenger Waiting Time (PWT). Previous studies (Niu and Zhou, 2013; Barrena *et al.*, 2014) have focused on reducing PWT based on the passenger arrival process at stations with either a uniform process or a Poisson process. Other study (Martinod *et al.*, 2019) proposes a stochastic optimisation model for integrating service and maintenance policies in order to solve the queueing problem and the cost of maintenance activities for UPT, with a particular focus on urban ropeway systems. But, these previous works have considered only single transport line without a Public Transport Network (PTN) context. Our work analyses the intermodality effects integrating a study focused on the mobility constraints on health emergency of pandemic cycles, in which the UPT lines undergoes a remarkable intensity of passengers' flow in one direction over defined periods –people go to work, students go to schools, etc.– generating a strong asymmetric demand of passengers over the PTN. Besides, the merit of our work is to develop a mathematical framework for integrating the service policy of different UPT line modes minimising the PWT cost and considering interdependencies of the passenger demand on intermodal PTNs.

During pandemic cycles, local governments strongly use two constraint policies for contain the virus spreading: (i) social distancing and (ii) restriction of social interaction. Nevertheless, under operational conditions, increasing the social distancing decreases the transport capacity, and as a result increases the PWT; however, increasing the restriction of social interaction decreases the transport demand, and as a result decreases the PWT. The aim is to optimise the PWT for long-term cost of operational service considering regulatory policies. Main contributions of this work can be summarised as follows:

- (i) this is the first work that develops a mathematical framework to model multimodal PTNs (comprised by a set of metro, tramway, and ropeway lines) based on stochastic optimization processes that integrate both service restrictions and passenger demand constraints generated by the health emergency, with the aim of solving the travel time; and
- (ii) this work proposes a dynamic discrete event model that use interrelated queuing processes to formulate the service problem using a cost-based expression.

Governments and transport operators do not know for certain how long these measures will last and whether or not subsequent waves can be expected. In this viewpoint we offer a service policy optimization for PTNs considering constraints for pandemic health emergencies. The remainder of this work is organised as follows: in Section 2 we expose the detailed problem formulation for different UPT line modes. A stochastic optimisation model for obtaining the optimal service is developed in Section 3. Section 4 presents a case study focused on a passenger demand that was performed at a mass transport system, which consists of a collaborative relationship between metro, tramway and ropeway lines. Finally, Section 5 discusses the results of the research.

Transport operators should consider the service policy. For the remainder of this work, the term service policy refers to the set of operational parameters which affect the passenger service such as vehicle capacity (number of available seating places and standing up places), vehicle density (number of service vehicles on a line), nominal vehicles' speed, distance between the vehicles, and vehicle frequency, which all of these affect the PWT.

2 PROBLEM FORMULATION

Taking an Intermodal Collaborative Transport Network (ICTN) perspective assumes that any transport network is more than the sum of its UPT lines (Paulsson et al., 2018). Collaborative transport involves a linked-work PTN, in which the different services policies of each UPT lines are integrated (Ceder, 2007), e.g., (i) a synchronisation between arrival and departure times becomes important in an intermodal transfer station, i.e., users of UPT lines are negatively inclined to transfer if it involves uncertain waiting time, (ii) the flow of users for a UPT line is accommodated by another one, and (iii) the service quality of a UPT line not being affected by the service of another

one. From this perspective, the facilitation of intermodal transfers is a key component in achieving full integration of PTNs (Nesheli et al., 2015).

An efficient service of ICTNs should consider the PWT cost. We propose a cost-based approach to quantify the performance of the service policy for each UPT line. This approach has an impact on the passengers' perceptions related to travel comfort (quality on the trip) and economic savings (PWT) as well. Therefore, the cost-based approach represents a comprehensive study through a quantitative analysis, which focuses on user experience during the trip. We analyse the transport demand to evaluate the proper service oriented to users, based on the fact that the queuing theory allows to evaluate the quality of service concerning the requested services. The probability function of passenger arrivals on the j th platform belonging to the i th UPT line behaves as a compound Poisson process $Pa_{j,i,n}$ (Gillen and Hasheminia, 2013) and take values from a finite set of events; thus, given $Pa_{j,i,n}$ as a probability function of discrete-time, the sequence $n = \{1, 2, \dots, N\} \forall n \in t$ is defined as the time sequence between successive events, over each i th UPT bi-directional line, with J stations and platforms designated as $j = \{1, 2, \dots, 2J\}$, where the start terminal and return terminal are indexed as station 1 and station J , respectively (see Figure 1).

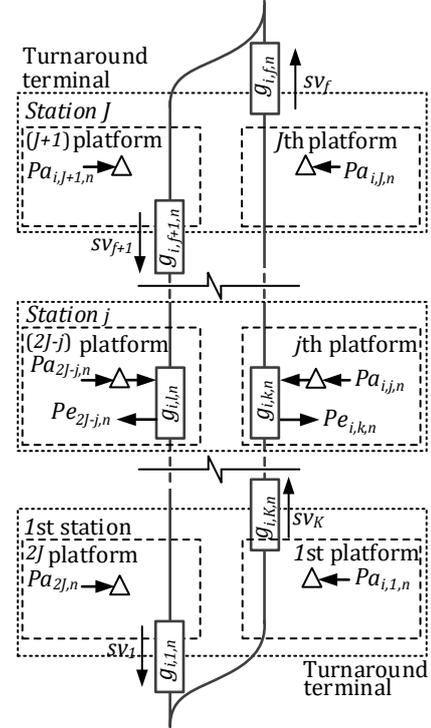


Figure 1: i th UPT line diagram belong to an ICTN.

The discrete-event model deals with the analysis of the PWT aiming to determining its global mean, Wg_i . The proposed model describes the queuing behaviour by means of the ratio between the number of users in the queue, $Lq_{j,i,n}$, and the passengers boarding, $\mu_{j,i,n}$, at the j th platform belonging to the i th UPT line over the n th discretised time

$$Wg_i = \sum_n \left(\mathcal{F}_i \sum_j \frac{Lq_{j,i,n}}{\mu_{j,i,n}} \right) \quad (1)$$

where $\mathcal{F}_i = f_{j,i,n}^{-1} \forall i \in$ (metro or tramway lines) and $\mathcal{F}_i = (sv_{k,i,n} dv_{i,n})^{-1} \forall i \in$ (ropeway lines), with $f_{j,i,n}$ as the frequency of vehicle arrival at the platforms, $sv_{k,i,n}$ as the commercial vehicle speed, and $dv_{i,n}$ as the number of vehicles giving commercial service in the i th UPT line.

The discrete-event model is comprised of a set of interrelated queues between UPT lines at the transfer stations (see Figure 2), where κ defines the relationship between the queuing users and the different UPT lines for the ICTN

$$Lq_{j,i,n} = Pa_{j,i,n} + \kappa \sum \sigma_{j',i',n} \forall j' \neq j \quad (2)$$

The optimal service plan is obtained by minimising the expected Wg_i cost, which represents the basis to assess the set of penalty costs for PWT to the i th UPT line. Formally, the problem is solved through a cost-based model made up of passenger waiting cost, Γ_i . The general relationship to describe the cost function for PWT is expressed as

$$\Gamma_i = f(Wg_i). \quad (3)$$

Methodologies to obtain Γ_i are directly defined by the operation managers of each UPT line, which is quantified in monetary units [mu]. Each UPT line can use different criteria to quantify the penalty cost according to its service policy.

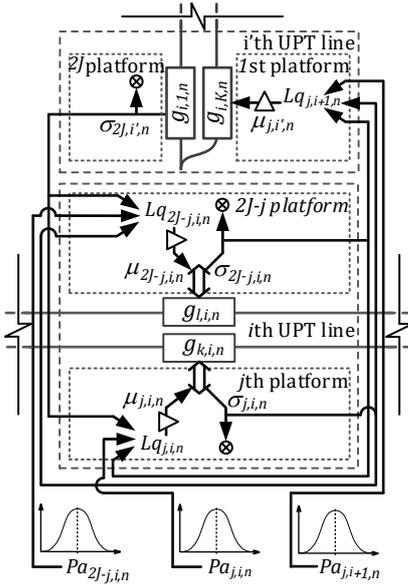


Figure 2: Transfer station between UPT lines.

3 OPTIMISATION PROCESS

A discrete-event formulation is used to describe the queuing, in which the passengers: (i) request a service, $\lambda_{j,i,n}$; (ii) wait in a queue, if necessary, Wg_i ; (iii) are serviced, $\mu_{j,i,n}$; and (iv) arrive at their destination, $\sigma_{j,i,n}$. The discrete-event model aims to determinate the Wg_i value considering a set of interrelated queues. This work introduces a stochastic optimisation model for improving the service

behaviour of ICTNs by means of the cause-effect relationship between the different service/operational policies for its UPT lines. The objective function related to the service policy cost can be expressed as

$$C^* = \min_n \sum_i \Gamma_i, \quad (4)$$

subject to the following constraints

$$0 \leq g_{k,i,n} \leq cv_{k,i,q}, \quad \forall k, i \quad (4.a)$$

$$0 \leq \mu_{j,i,n} \leq Lq_{j,i,n}, \quad \forall j, i, n \quad (4.b)$$

$$0 \leq \sigma_{j,i,n} \leq g_{k,i,n}, \quad \forall j, i, n \quad (4.c)$$

$$fl_i \leq f_{j,i,n} \leq fu_i, \quad \forall j, i, n \quad (4.d)$$

$$dl_i \leq dv_{i,n} \leq du_i, \quad \forall i, n \quad (4.e)$$

$$0 \leq Wg_i \leq Wu_i, \quad \forall i \quad (4.f)$$

$$\sum_{j,i,n} \lambda_{j,i,n} = \sum_{j,i,n} \sigma_{j,i,n}, \quad (4.g)$$

$$0 < k, j, i, n, \quad (4.h)$$

where:

Eq. (4.a) highlights that the occupied places in a vehicle, $g_{k,i,n}$, must be lesser than or equal to the vehicle's capacity, $cv_{k,i,q}$; Eq. (4.b) means that $\mu_{j,i,n}$ must be lesser than or equal to $Lq_{j,i,n}$; Eq. (4.c) expresses that the number of passengers disembarking from the vehicle, $\sigma_{j,i,n}$, must be lesser than or equal to $g_{k,i,n}$; Eq. (4.d) is related to an operational condition, which $f_{j,i,n}$ is limited by the range $[fl_i, fu_i]$; Eq. (4.e) refers to another operational condition, which is the system must have a range of vehicles in commercial service $[dl_i, du_i]$; Eq. (4.f) is related to a service policy, where Wu_i is the upper limit of the global PWT; Eq. (4.g) indicates that at the end of a full working day, all passengers are served and no one remains within the system.

4 CASE STUDY

This case study is applied to urban public transport network belonging to the ICTN of Medellín city (Co). This ICTN is a rapid transit system mainly comprised of two metro lines, a tramway line and four ropeway (*télcabine*) lines, which are interconnected by means transfer stations for the intermodal connections (see Figure 3). This ICTN has 27 Metro stations, 15 ropeway stations, and 9 tramway stations/stops for a total of 79 stations (+14 stops). All lines operate for 20 hours a day, 7 days a week and 360 days in year.

A set of field measurements, called Origin and Destination Analysis (ODA), were conducted for establishing the passenger demand profile during a typical working-day on 16 August 2018. This date was selected because it was a part of a large-scale measurement protocol for the Medellín metropolitan area, when there were no disturbances (no holidays, no collective vacations, no festivals and no religious ceremonies) during a long time period. During this typical working day, the passenger demand profile has significant fluctuations; thus, it is possible to distinguish that the morning rush hour starts at 5a.m. and ends at 7a.m., while the evening rush hour starts at 5p.m. and

ends at 8p.m. The characteristics of each line are discussed hereafter.



Figure 3: ICTN main lines of Medellín city.

4.1 Metro lines

The metro lines are similar to suburban ET420 trains, it first opened for service in 1995 (Castañeda et al., 2012; Martinod et al. 2012). The vehicle traction in half-load conditions ($5,5 \text{ pax}/\text{m}^2$) is $0,95\text{m}/\text{s}^2$ and in full-load condition ($8\text{pax}/\text{m}^2$) is reduced to $0,85\text{m}/\text{s}^2$. The vehicle braking in service is in a range $[1,6 - 1,7]\text{m}/\text{s}^2$ (Bernal et al, 2016; Martinod et al., 2016). They are comprised by two lines:

- (i) *Línea A* crosses the metropolitan area from North to South, which is $25,8\text{km}$ long and serves 21 stations; and
- (ii) *Línea B* crosses the metropolitan area from downtown to the western district, which is 5.5 kilometres long and serves 6 stations (+1 transfer station with *Línea A*).

4.2 Tramway line

The tramway line (*Línea TA*) is a Translohr rubber-tyred tram system. It started trial operations in 2015 and serves as a feeder line built to connect two ropeways lines (*Línea M* and *Línea H*) from eastern district of the city to a metro line (*Línea A*) at downtown. *Línea TA* runs $4,3\text{km}$ with 3 tramway stations (+6 stops).

4.3 Ropeway (télécabine) lines

The ropeway lines belong to a fleet of passenger cable cars comprised of a gondola-type aerial cable on a continuous cycle (Martinod et al., 2014). Both lines are similar in design and construction to those used for passenger tourist transports in winter regions, but serve completely different functions than those for tourists (Martinod et al. 2015). They are comprised by four lines:

- (i) *Línea K* provides mobility to the northeaster district of the city since 2004. Its commercial max. speed is $18\text{km}/\text{h}$ and the system capacity is $3000\text{pax}/\text{hour}$ per direction, spread over 90 cable cars;
- (ii) *Línea J* has been operating since 2008. It crosses the central-western district over south-north direction, with a total length of $2,7\text{km}$. It has a maximum capacity of $3000 \text{ pax}/\text{hour}$ per direction with 119 cable cars, a travel time of 12min. , with a max. frequency of 12sec. between cable cars and a commercial speed of $18 \text{ km}/\text{h}$;
- (iii) *Línea M* crosses an area of the central-eastern zone of the city from south-north direction, in a total length of $1,05 \text{ km}$. It has a max. capacity of $2500 \text{ pax}/\text{hour}$ per direction, 51 cable cars, a travel time of 4min. , with a maximum frequency of 9 seconds between cable cars and a commercial speed of $18 \text{ km}/\text{h}$; and
- (iv) *Línea H* was inaugurated in 2016. It crosses an area of the central-eastern zone parallel to *Línea M*, in a total length of $1,4\text{km}$. It has a max. capacity of $1800 \text{ pax}/\text{hour}$ per direction, 44 cable cars, a travel time of 5min. , with a maximum frequency of 13sec. between cabins and a commercial speed of $18 \text{ km}/\text{h}$.

4.4 Mobility constraints on health emergency

In March 2020, the World Health Organization (WHO) declared the Covid-19 virus outbreak as a pandemic. The spread of the virus has resulted in a set of variable measures, which have become the new norms:

- (i) social distancing that involves urban transport capacity constraints, Tc , i.e., the transport system capacity (stations, stops, and vehicles) has been limited; and
- (ii) restriction of social interaction, Pd , a lot of people have been temporarily unemployed or work from home, and most out-of-home (leisure) activities have been cancelled; thus, passenger demand decreases.

The proposed method provides a stochastic model optimization based on passenger demand analysis, which is applied to a commercial ICTN subject to two regulatory policies for pandemic social isolation: (i) a social distancing

constraint and increasing the passenger demand restriction is the approach to obtain the local optimum. Thus, the hard confinement policy should be modified to $C^* = \langle Tc, Pd \rangle^* = \{84, 91\}\%$, and the mandatory confinement policy should be modified to $C^* = \langle Tc, Pd \rangle^* = \{78, 81\}\%$.

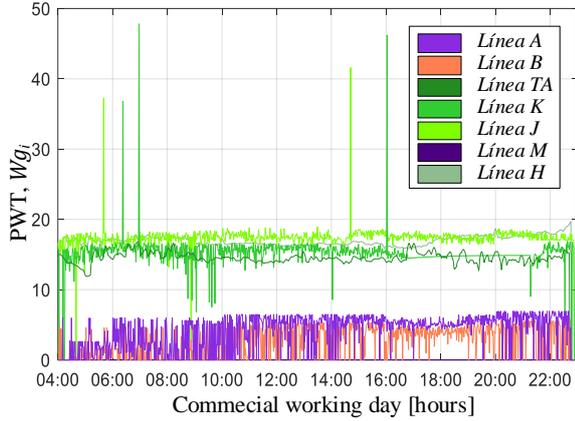


Figure 6: PWT for flexible isolation policy.

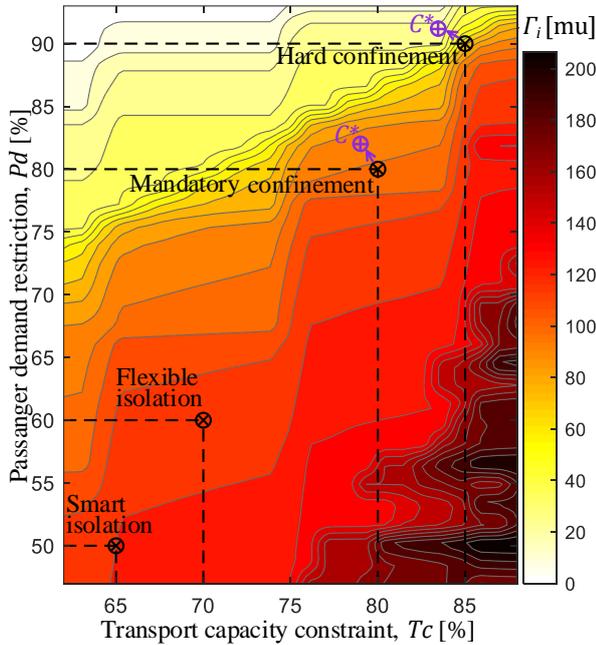


Figure 7: General PWT cost of the ICTN for social isolation level, $\sum_i \Gamma_i$ [mu].

6 CONCLUSIONS

A making decision tool was developed for considering the mobility constraints on health emergency of pandemic cycles to solve the problem of PWT costs involved in different UPT line into ICTNs.

The proposed method provides a stochastic discrete-event model optimization based on passenger demand analysis, which is applied to a commercial ICTN subject to two regulatory policies for pandemic social isolation: (i) social distancing that implies urban transport capacity constraints, and (ii) restriction of social interactions affecting passenger demand.

In the first stage of the work, an ICTN model (two metro, a tramway and four ropeways lines) was developed for obtaining a queue process based on numeric simulations, one that considers the interdependencies and asymmetries of passenger demand. In the second stage, a set of regulatory policies for health emergency of pandemic cycles was integrated to the numeric model. In the final stage of our research, we solve the service problem via a cost-based expression for obtaining a queue process of optimization.

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